Welding and cutting in the new millennium
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Challenges for welding consumables for the new millennium

by Lars-Erik Svensson and Johan Elvander, Esab AB, Göteborg, Sweden

A rc welding was invented around 100 years ago and, at least during the past 50 years, it has been the main fabrication method for structures made of steel and other metallic materials. There are several arc welding processes, which means that there are many possible ways to optimise the welding operation. With many of the methods, the mechanisation of the process is possible and this can decrease the cost of welding. With the large number of consumables available, the flexibility required to achieve appropriate properties in the welded joint is very high.

The potential for adjusting the chemical composition of the weld metal is almost unlimited. By using different flux systems, welding characteristics such as drop transfer, arc stability and the fluidity of the molten metal can be controlled.

However, to maintain profitability, industry must always look for ways of improving and rationalising working processes. As welding is such a central process for many fabricators, the welding operation has been the focal point for many of the improvements which have been made over the years. These improvements can be categorised into three main groups:

- developments in design
- development of welding processes
- developments in materials

Of course, these developments cannot be seen in isolation but...
are interrelated. In order to discuss possible future developments, it may, however, be helpful to make this division.

Design developments fall outside the scope of this paper, but it can be briefly stated that, with the introduction of high-speed computers, finite element calculations of critical details in a structure have become a standard tool, helping to optimise the construction significantly. A thorough design is traditionally conservative, due to the major consequences of a failure, there is definitely a trend towards utilising materials such as higher strength steels or aluminium to produce lighter structures with a high load-carrying capacity. In this context, it must be realised that one of the controlling factors in design is fatigue, which is a limiting factor for the use of high-strength steels.

With the development of mechanised welding, it is more advantageous to use fillet welding rather than butt welding. To implement this, the development of the welding processes took place primarily from 1930 and onwards. The most common processes like submerged arc welding, gas-tungsten arc welding and gas-metal arc welding were all developed more than 50 years ago. They have been further refined with the aid of sophisticated electronic components in power sources, elaborate handling devices like columns and boom and seam sensors. Many of the methods are now fully automated. The productivity of the processes has also been increased by a number of modifications. The best example is probably submerged arc welding, where productivity can be increased by using multi-wire systems or by feeding metal powder into the weld pool. In gas-metal arc welding, the use of cored wires has led to an increase in productivity. Here, too, modifications to the process, as in Rapid Arc and Rapid Melt, have acquired some degree of popularity. In parallel with the developments in productivity, consumables have also been developed to meet new and higher requirements. Three different situations have been encountered;

- higher strength and impact toughness as well as enhanced corrosion resistance is desired to match the development of steel;
- higher impact toughness at lower temperatures is needed for structures operating in harsh environments to maintain strength and toughness for welds deposited with higher productivity (which generally means higher heat input and coarser microstructures).

A rc welding has been established for many years as the leading joining process. In certain applications, other processes have acquired increasing popularity. In the automotive industry in particular, many other joining processes, such as adhesives and laser welding, have taken over from traditional arc welding. In most other circumstances, arc welding is still the leading process, despite the fact that many other processes have been developed. In recent years, two other processes, laser welding and friction stir welding, have been introduced and developed to such an extent that they can be regarded as realistic challengers to arc welding. The benefits to the user of these processes are that they are often performed in just one or two passes, even for relatively thick material, and that the distortion of the plates is very small, resulting in far less work for rectification. The drawbacks are the large investment costs and the need for much closer fit-up of the plates. In the case of laser welding, special grades of plates are needed and, in the case of friction stir welding, the supplementary equipment for handling the plates is quite extensive. In the large research projects that have been run or are still in progress and in which these processes are being evaluated, other drawbacks have also been noted. The ductility of laser welds is usually lower than that found in arc welds and, due to the very high cooling rates, martensite is often formed both in the heat affected zone and in the weld metal. Friction stir welding is still very much more at the development stage and has only been used commercially for welding aluminium, with very promising results. It is still not known whether it will be possible to use this process for steels on a larger scale.

**Process development**

The relative use of different welding consumable types, measured in terms of weld metal consumption, for welding structural steel between 1975 and 1996 is shown in Figure 1. The figure shows the development for three regions: Western Europe, the USA and Japan.

The use of covered electrodes has been replaced by methods producing higher productivity. M IG/M AG welding, using solid wires, has captured the largest market share. The consumption of tubular wire was less than 5% for many years, but, during the last few years, it has increased markedly and is now almost 10%. This consumption is expected to continue to increase rapidly.

The decrease in the use of covered electrodes is expected to be less dramatic in the years to come, although some further decrease can still be foreseen. The growth of tubular wires will then be due in part to a change in process from covered electrodes, but it will mainly result from the replacement of solid wires with tubular wires.

The major change which is currently taking place is the increasing use of welding robots and other forms of mechanisation. This trend is particularly strong in countries with high labour costs, but another, equally important factor is the difficulty involved in finding qualified welders who are willing to perform manual welding. It has, in fact, been found that the wear and tear experienced by welders, especially when welding with semi-automatic processes, can be quite high. To address this situation, two possible methods can be considered: either fully mechanise the operation or introduce another method which imposes less weight on the welder’s arms and shoulders. The second method has sometimes been
used. One example of this comes from Norway where, in a particular application, MMA welding with high-recovery covered electrodes replaced semi-automatic welding. It was actually found that productivity was not reduced but was instead enhanced. The lesson to be learned here is that there are several ways of achieving high productivity. High flexibility and a careful analysis of the different options is most likely to promote the optimum choice, which will in turn lead to maximised productivity.

Environmental questions have attracted increasing interest in modern society. The demand for more environmentally-friendly operations has been stepped up — in the welding industry and other areas — in the welding industry and other areas. Esab has played an active part in improving the situation with regard to the impact on the environment from many parts of its operations. Details about Esab’s environmental activities can be found in (1). A new report describing further improvements will be issued in 1999.

The main welding process in Figure 1 is MIG/MAG welding with solid wire. This is not surprising, due to the combination of flexibility, productivity and quality the method offers. The latest developments here are related to the packaging system. For applications with high duty cycles, the introduction of Marathon Pac was a major improvement. Marathon Pac has been further refined and is now made of recyclable material. Using a special system, the wire always comes out straight, producing extremely low friction in the wire conduit. With a new and improved design, 12 m long wire conduits are used. When starting, only the free wire needs to be accelerated, thereby reducing the wear on the drive rollers. The straight wire is a major benefit in different situations when the wire has to be positioned carefully (e.g. welding in narrow gaps) or when welding in thin plate, for example. When using robot welding, joint tracking is critical and the straight wire makes this much more accurate.

The most important benefit of Marathon Pac is, however, the opportunity to increase productivity. The number of bobbin changes is reduced significantly, repairs and rejects are reduced and it is possible to run unmanned shifts during the night.

Further improvements on the packaging side are expected. At present, Marathon Pac is available in two sizes. The serial connection of several Marathon Pacs, to reduce the number of changes, has also been tested with promising results.

The most important factor for a fabricator using robotic welding is that the robot can run continuously. This in turn leads to requirements being imposed on the equipment and consumables, together with high and consistent quality to create the conditions necessary for problem-free operation.

For the wires at a robot welding station, feedability and ease of arc striking are essential properties. The new robotic wire, PZ 6105R, from Filarc is one example of this development. Most robots are designed for solid wires, but they can be changed relatively simply to cored wires and the different parameter settings that are needed. The advantages of metal cored wires compared with solid wires are the higher welding speeds that can be attained, the improvements in penetration and the reduction in spatter.

As soon as a robot is installed, the handling time is more or less constant, independent of the choice of process. So, the only way to increase productivity still further is to increase the welding speed (e.g. use of cored wires). The higher and broader penetration in fillet welds produces a
larger safety margin for the construction and the opportunity for wider tolerances in the fit-up. There are also discussions about whether it is possible to take account of the penetration when calculating the throat thickness. This would add a further benefit to the cored-wire process and would also be a significant cost-reduction factor. Another important factor is the bead shape, which is much smoother for the cored-wire process. The transition between the weld metal and the base material is also much smoother with cored wires, something that is very important for constructions subjected to fluctuating loads. The low spatter reduces the need for post-cleaning to a minimum, thereby enabling welded parts to be immediately transported to the next link in the manufacturing chain.

There are some further developments in the MAG process (twin-arc MAG and tandem MAG) which may be of significant interest for the future. In twin-arc MAG, two wires are fed into the same torch and connected to a sophisticated power source. The wires have the same voltage, but different feeding rates. By pulsing, disturbances between the arcs are avoided. This process produces extremely high deposition rates. The process has also been tested with metal cored wires (PZ 6105R and OK Tubrod 14.13) with good results. Submerged arc welding has had a fairly stable share of the market over the years. It is a high-productivity process and the applications are therefore often associated with heavy industry. A number of improvements have been made for even higher productivity, such as increasing the number of welding wires. One relatively new development involves using a tubular wire instead of a solid wire. This increases the deposition rate, improves the penetration profile and makes the adaptation of chemical composition much easier. The process is now being further optimised, with the joint development of the cored wire and the flux, to provide a better process. One further example of development within this field is the use of a cold wire, which is fed separately but in synchronised form, into the weld pool. This feature both increases productivity significantly and helps to cool the weld, thereby preventing excessive grain growth. A patent for this process has now been filed by Esab.

In the future, it is expected that, in the case of assembly welding, especially for heavy equipment, covered electrodes will still be used. The use of tubular wires will increase significantly, especially in Europe. Tubular wires will replace covered electrodes, as well as solid wires to some extent. The main developments will be seen in tubular and solid wires, particularly in connection with mechanised welding. For the technically most advanced fabricators, sophisticated methods like laser welding will be introduced. For fabricators who cannot invest the very large amount of money required for lasers, advanced methods like twin-arc MIG, which is still based on relatively conventional power sources, but with advanced software, could be one possible way of increasing productivity. However, the majority of fabricators are small and medium-sized enterprises and, as a result, conventional welding methods will still be used. Productivity will then be obtained from using more efficient consumables.

**Developments in structural steel**

The large advance in terms of the weldability of structural steels came with the introduction of the thermo-mechanically (TM) processed steels at the beginning of the 1980s. Compared with the traditional normalised steels, the new steels had a much leaner composition, for the same yield strength. The carbon content in particular was reduced and the strength was obtained from finer grain size and increased dislocation density. Sometimes, accelerated cooling was used, adding extra strength as the steel transformed to bainite rather than ferrite.

In addition to the lower carbon content, the quality of the steels was improved significantly by a reduction in the impurity element (sulphur and phosphorus) content.

It is difficult to envisage a similar major development in steels in the near future. Slow and continuous improvements will probably be made to TM steels — in terms of their impact properties, for example — and they may find new applications, but, as there will probably be no major changes, there will be no need to make any significant changes to the consumables used for welding these steels.

In the new European standard EN 10 113-3, TM steels with yield strengths of up to 460 MPa are specified. TM steels can now be produced at many steelworks. What might differ between suppliers is the combination of plate thickness and yield strength that can be delivered. Many of the steels supplied with yield strengths of up to approximately 500 MPa are made using the TM process. For the highest strength levels in this range, the production process is determined by the plate thickness. For thinner plates, the TM process can be used, but for heavier plates it is necessary to use quenching and tempering to obtain the properties. Above approximately 500 MPa, all steels are of the QT type. These steels are also of high quality, with a low impurity content and good weldability. However, with increasing strength levels and increased thickness, more alloying is needed, making preheating necessary.

A trend that has continued for some years involves using steels of higher strength. The advantage of this is obvious: structures can be made with thinner plates, reducing the weight and thereby improving the opportunity for higher loads. It should be noted that there are situations in which a structure cannot take advantage of thinner plates, such as when buckling, stiffness or fatigue strength is the design criterion.

High-strength steels are commonly defined as steels with a...
Table 1. Hydrogen content of different consumables.

<table>
<thead>
<tr>
<th>Consumable type</th>
<th>Hydrogen content (ml/100 g weld metal)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic covered electrodes</td>
<td>5</td>
<td>3 ml for special types</td>
</tr>
<tr>
<td>Tubular wires, basic</td>
<td>&lt; 5</td>
<td></td>
</tr>
<tr>
<td>or metal cored</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubular wires, rutile</td>
<td>&lt; 10</td>
<td>often &lt; 5</td>
</tr>
<tr>
<td>Submerged arc fluxes</td>
<td>&lt; 5</td>
<td></td>
</tr>
</tbody>
</table>

yield strength of more than 350 MPa. These steels now have found their way into many areas of construction. In several new spectacular bridge constructions, TM steels with yield strengths of 420 or 460 MPa have been used. One example is the Great Belt bridge in Denmark which was built during the mid-1990s and recently went into operation. Part of the bridge is made in the form of a steel suspension bridge, using some 80,000 tonnes of steel. Half this amount is accounted for by TM steels, with a yield strength of 420 MPa. Details of the building of this bridge are presented in (2).

Another example from the bridge sector, in which a very high-strength QT steel is used, is the world’s largest suspension bridge, the 1,990 m long Akashi bridge in Japan. The construction of this bridge was completed in 1997 and the bridge is now in operation. In the box girders of this bridge (comprising hundreds of tonnes of the steel), a very high-strength steel, HT780, with a yield strength of more than 780 MPa was used. It is particularly interesting to note that this steel only needed less than 50°C of preheating, despite its high strength, due to the elaborate alloying technique, combined with the quenching and tempering technique (3).

Examples of applications for high-strength steels with yield strengths of up to around 500 MPa include standard structural steelworks, excavator equipment, pipelines, cranes, roof support in mines and, of course, offshore constructions.

Steels of higher strength such as 690 MPa are used for trailers for heavy haulage work, cranes with a high lifting capacity, dumper bodies and so on. For steels with even higher strength (900 MPa and above), typical applications include penstocks, conveyor systems and mobile bridges.

For steels with a yield strength of 350-450 MPa, there are usually very few welding problems. The problems that can arise here include low toughness in the weld metals, often associated with increased nitrogen content, due to the use of too long an arc. If low hydrogen consumables are used, hydrogen cracking is very rarely a problem. If it arises, it is related to the welding of heavy plates. Solidification cracking may occur in very special circumstances, but it should generally pose no problems. Impact toughness in high-dilution welds, such as one-sided welding with only one bead, can sometimes be low. This is, however, often due to some incompatibility between the base metal and the consumable.

It is not until steels with a yield strength of 600 MPa or above are used that welding may become somewhat problematic and require more caution. The steels are used in demanding applications, requiring good toughness at low temperatures in many cases. In this case, two problems may occur. The first involves finding a weld metal with a yield strength higher than that of the steel and at the same time possessing good impact toughness. There are an increasing number of consumables with these properties, but there may still be problems when it comes to combining high productivity and good mechanical properties. This is discussed in more detail in the paper by L-E Svensson in this issue.

The second problem is related to hydrogen cracking. With the steel developments that have taken place, including a lean alloying content, the weldability of the steels has been increased. In particular, the need for preheating has been reduced dramatically. This is especially true of steels of lower strength, such as 350–500 MPa steels. For these steels, the weld metals are also lean in alloying content and do not require preheating. However, when it comes to the high-strength steels, the situation is more complicated. The only way to increase the strength of these weld metals is to increase alloying. The advanced processing routes used for the steels can naturally not be applied to the weld metal. So, in a situation in which there is less hardenability in the HAZ than in the weld metal, there may be several reasons why hydrogen cracking would be more likely to occur in the weld metal. Preheating must then be prescribed to protect the weld metal rather than the HAZ of the parent plate. This is a somewhat new situation and, although fabricators have learnt how to handle it, there is a lack of fundamental knowledge about weld metal hydrogen cracking which must be remedied.

One solution that might appear to an attractive means of resolving this situation is a further reduction in hydrogen content from the consumables. Developments in which the hydrogen content of the weld metals has been reduced have already been in progress for many years. As was noted in a previous paper (4), hydrogen contents as specified in Table 1 have been obtained as a result of intensive research and development during the past decade.

There are several reasons for believing that the rate at which this downward trend will continue will be slower in the future than it has been in the past. It will be increasingly difficult to make further reductions from the very low levels that have already been achieved. The hydrogen content can be reduced by a number of measures. Unfortunately, these changes often tend to have a negative effect on other properties,
such as welding characteristics. So, a further reduction in hydrogen will lead to consumables which are less attractive to the welder. This factor has to be taken seriously and evaluated against the benefits of a further reduction in the hydrogen content. Another important factor is how accurately the measurement of hydrogen content can be made. Investigations have shown that the error is around 0.5–1.0 ml/100 g weld metal for the gas chromatography method. The relative error at, say, 2 ml hydrogen/100 g weld metal is then 25–50%. It must be noted here that the large errors are not due to the analytical equipment but instead to variations in the specimen preparation phase.

Apart from hydrogen stemming from the consumable, there are other sources of hydrogen, such as the surrounding atmosphere, the base material or dirt and oil on the plate and joint surfaces.

So, the amount of hydrogen in the weld pool can differ from the hydrogen content specified by the electrode manufacturer. Naturally, the hydrogen content of the consumable is also affected by the possible moisture absorption. Although low moisture absorption electrodes have been developed, some absorption always takes place. This can be avoided by using vapour-tight packaging, like Esab’s VacPac. In this kind of packaging, the electrodes are kept in the same condition as they were manufactured until the package is opened.

To benefit fully from the development of steels, to increase productivity during welding, systematic investigations need to be made, partly to be able better to define the preheating necessary for safe welding, but also in order possibly to develop the weld metals further with the aim of making them crack-resistant while maintaining the mechanical properties.

### Developments in heat-resistant steels

The steels which are traditionally used for high-temperature applications within the petrochemical industry or the power generating industry can broadly be classified into two groups. One group, specified in EN 10 028-2 Steels for pressure purposes, with specified elevated temperature properties, contains those steels commonly found in high-temperature power plants. In this standard, there are first four unalloyed quality steels, with a yield strength varying from 235 to 355 MPa. The properties of these steels are specified up to 400°C. For use at higher temperatures, steels alloyed with molybdenum and chromium are used. The simplest steel is only alloyed with about 0.3% molybdenum. The most common steels are alloyed with either 1.25Cr-0.5Mo or 2.25Cr-1Mo. These steels have their tensile properties specified up to 500°C. The maximum operating temperature is 565°C. The creep properties, given as reference in the standard, are specified up to 600°C for a 2.25Cr-1Mo steel (10 CrMo 9-10).

There are a number of suggestions on how to modify the 2.25Cr-1Mo steel in particular. The most frequent suggestions are to increase the chromium content, so that the typical composition would be 3Cr-1Mo instead, and to add vanadium. The addition of vanadium increases the high-temperature strength effectively, but the cracking risk in the HAZ is increased.

Consumables for welding these steels have much the same composition as the parent material. The microalloying elements vanadium and niobium are on a lower level than they are in the steel, thereby reducing the creep strength of the weld metals somewhat. Since the microstructure of the weld metal is bainitic, the prior austenite grain boundaries are preserved and may be a source of embrittlement. In general, the welded joint is annealed after welding, to improve toughness and reduce residual stresses. In common with other similar microstructures, the weld metals can suffer from two types of embrittlement. During annealing, which typically takes place at 690°C, carbides can precipitate on the prior austenite grain boundaries and this can lead to lower toughness. This is called irreversible embrittlement, as it is difficult to remove the carbides. At lower temperatures, typically 400-500°C, reversible embrittlement may occur. This is due to the segregation of impurity elements, like phosphorus, to the prior austenite grain boundaries. This process may take place either during slow cooling through the critical temperature regime or if the construction is operating at this temperature, as is common in the process industry, for example.

To prevent reversible embrittlement, it is important that the phosphorus content is reduced to the absolute minimum. The degree of segregation and embrittlement is also influenced by other elements and formulae have been developed to help control the permissible content of various elements. The best-known of these formulae is the Bruscato X-factor (5).

For more demanding applications, steels with higher alloying contents are used. The steel with

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Minimum preheating temperature °(C)</th>
<th>Max interpass temperature °(C)</th>
<th>Post-weld heat treatment (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 Mo</td>
<td>75 (t &gt; 15 mm)</td>
<td>250</td>
<td>600-650</td>
</tr>
<tr>
<td>1Cr-0.5 Mo</td>
<td>100 (t &gt; 15 mm)</td>
<td>300</td>
<td>650-750</td>
</tr>
<tr>
<td>2.25Cr-1Mo</td>
<td>200 (t &gt; 15 mm)</td>
<td>350</td>
<td>(all thickness)</td>
</tr>
<tr>
<td>9Cr-1 Mo</td>
<td>200 (all thickness)</td>
<td>350</td>
<td>700-770</td>
</tr>
<tr>
<td>12Cr-1Mo</td>
<td>350 (all thickness)</td>
<td>450</td>
<td>intercooling to 125-150</td>
</tr>
</tbody>
</table>
Developments in stainless steel

The use of stainless steels has been increasing worldwide for a long time and this trend is expected to continue. Apart from the common grades, significant developments have taken place when it comes to new grades with improved characteristics (see Table 3). Ferritic-austenitic duplex and superduplex, as well as superaustenitic steel, have been developed. One of the important driving forces behind the development of new stainless steel has been the need to improve characteristics in chloride-containing environments. This harsh environment gives rise to both pitting and stress corrosion cracking.

These types are now being used in increasing tonnages in the oil and gas industry, in the pulp and paper industry, in other types of process industry and in applications such as chemical tankers, for example.

Information about some austenitic, duplex, superduplex and superaustenitic steels is given in Table 3. Ferritic-austenitic duplex and superduplex steel have been developed. Some of the characteristics of these weld metals are detailed in the paper by E-L Bergqvist in this issue.

### Table 3. Examples of stainless steels, with typical compositions and properties.

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Chemical composition (%)</th>
<th>Tensile properties (N/mm²)</th>
<th>PRE *</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Austenitics</td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>ASTM 304L</td>
<td>0.02 18.5 9.5 - -</td>
<td>205 520 19</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>ASTM 316L</td>
<td>0.02 17.0 11.5 2.7 -</td>
<td>205 500 27</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>UNS NO8904</td>
<td>0.01 20.0 25.0 4.5 Cu</td>
<td>220 500 36</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Super-austenitics</td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>UNS S3125</td>
<td>0.01 20.0 18.0 6.2 0.20 Cu</td>
<td>300 650 43</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>UNS S3265</td>
<td>0.01 24.2 17.9 7.2 0.45 Cu</td>
<td>430 750 55</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Duplex</td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>UNS S31803/</td>
<td>0.02 22 5.5 3.0 0.18</td>
<td>480 680 35</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>S32205</td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Superduplex</td>
<td>0.02 25 7.0 4.0 0.28</td>
<td>540 780 42</td>
<td></td>
<td>--</td>
</tr>
</tbody>
</table>

*) PRE = %Cr + 3.3%Mo + 16%N

### Table 4 Duplex weld metals for MMA. The composition of the weld metals is representative of other welding processes as well.

<table>
<thead>
<tr>
<th>Consumables</th>
<th>Weld metal chemical composition (%)</th>
<th>Tensile properties (N/mm²)</th>
<th>FN</th>
<th>PRE</th>
<th>Impact toughness –60°C (J)</th>
</tr>
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<tr>
<td></td>
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</tr>
<tr>
<td>OK 67.55</td>
<td>0.03 22.0 9.0 3 0.17</td>
<td>645 800 30-45 35 45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OK 68.55</td>
<td>0.03 25.5 9.5 4 0.25</td>
<td>700 900 30-50 43 45</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The highest alloying content in this group is 12Cr-1Mo steel. However, most interest in recent years has focused on steels with about 9% chromium-1% molybdenum, where large-scale developments have taken place.

About 20 years ago, work began in the US on the development of a steel of the 9Cr-1Mo type, with high-temperature characteristics like those of a 12Cr-1Mo steel but far better weldability. Another aim was to be able to increase the operating temperature of power plants to around 600°C, thereby significantly increasing efficiency. The modification from the original 9Cr-1Mo steel lies primarily in the addition of vanadium, niobium and nitrogen. This modified steel has already found a number of applications, mainly in the form of pipes.

Developments in this field are rapid. There are suggestions for new steel compositions, like 9Cr-2Mo, or to replace molybdenum with tungsten. The aim here is further to improve the creep properties. These developments will call for the further development of weld metals. It is expected that, if the 9Cr type of steel continues to increase, by being used in the petrochemical industry, for example, this will be one of the most intensive and interesting areas of materials development in the years to come.

The weldability of Cr-Mo steels is limited and weldability deteriorates as the alloying content increases. Preheating and post-weld heat treatment are required to varying degrees for many of the steels. A summary of the recommendations for welding these steels is given in Table 2. For all steels, consumables with matching properties (and often very similar chemistry) exist, for all the common processes. Note that 12Cr-1Mo is an exception. This alloy is not welded using high-productivity methods. However, consumables for welding 9Cr-1Mo modified steels are still being developed.
er, susceptible to crevice corrosion in certain conditions (higher temperatures, de-aerated water, very high chloride content). To withstand seawater environments, like the North Sea, with a chloride content of around 21,000 ppm, the steels need to be improved still further.

Alongside the development of the duplex and super-duplex, a family of steels, known as super-austenitic steels, was developed. Some examples of these steels are given in Table 3. In typical cases, they contain around 20% chromium, 18% nickel, 6% molybdenum and 0.2% nitrogen. Chromium and molybdenum produce excellent corrosion characteristics, while nitrogen stabilises the austenite and reduces the risk of sigma phase formation during welding. The advantage of these steels is that they have better ductility and impact strength than the duplex and super-duplex steels. The yield stress of super-austenitic steels is, however, lower than that of duplex steels (of the order of 350 MPa). The corrosion resistance of these super-austenitic steels is more or less the same as that of the super-duplex steels, as is shown by the similar PRE values (Table 3).

In order to comply with extremely rigorous corrosion requirements, the super-austenitic steels have been improved still further. Examples of steels with higher PRE values include Alloy 31 from VDM and 654 SMO from AvestaSheffield. These materials are generally included among stainless steels, but they are sometimes on the borderline of nickel-based alloys.

Super-austenitic steels are not welded with consumables of the same type, as it is not possible to obtain sufficiently high PRE values with these weld metals. The principal problems are caused by the molybdenum content. Molybdenum segregates heavily during solidification and the areas which are poor in molybdenum have a far lower PRE value than the parent metal. Nor is it possible to compensate for the molybdenum with other alloying elements, as this leads to a significant risk of intermetallic phase precipitation. Consumables of the nickel-base type are used to weld these steels. The most common type is Ni-21Cr 9Mo 3 Nb, which is used for most welding processes. Potential problems with this composition are hot cracking and the precipitation of intermetallic phases. To avoid this, a low heat input and low interpass temperature should be used and dilution should be restricted. A better choice may be to use the recently developed alloy Ni-23 Cr 16Mo instead (6).

Very recently, the development of stainless steels for offshore activities has taken a different route. For cost-saving reasons, and due to increasing experience of the corrosion potential of the media that are transported, there is an initiative to develop so-called super-martensitic steels and weld metals. These steels, which have a range of composition of around 10-13 % Cr, 2-4% Ni and 0-6% Mo, all with an extremely low carbon content, are now the subject of intensive research and development programmes. More information on these steels is presented in the paper by L Karlsson in this issue.

Another trend that has emerged relatively recently is the attempt to improve the weldability of steels at the lower end of the stainless steel range, namely steel with a chrome content of around 10-12 %. These steels are interesting for use in the transport sector.

The most popular method for welding stainless steel is manual metal arc, followed by MIG using solid wires. However, with solid wires, there is a greater risk of weld defects, such as lack of fusion. Cored wires, which have recently been developed for many of the common stainless steel grades, improve this situation significantly. Productivity is enhanced by about 30% and spatter is significantly reduced. Cored wires have been developed for both downhill and out of position welding.

**Developments in aluminium**

Aluminium is finding more widespread use in most engineering structure segments. The new high-speed ferries for Stena Line between Sweden and Denmark and across the Irish Sea are good examples of the way aluminium is being utilised to obtain a lighter weight to permit either a higher load-carrying capacity or faster speeds. However, the use of aluminium has also made it necessary to redesign the ferry construction.

The advantages of aluminium as an engineering metal are obvious; it is a light and yet comparatively strong material, with relatively good corrosion. It is also environmentally-friendly, in that it is recyclable. There are also some drawbacks to aluminium; the lower Young’s modulus makes it less stiff, the high thermal expansion coefficient induces handling problems during welding and straightening operations and large amounts of energy are required for the production of raw aluminium.

The drawbacks to aluminium mentioned above, combined with other things, like the loss of strength in the heat affected zone during welding, are making design and fabrication in aluminium different from that in steel.

The difference compared with steel can be clearly seen when welding aluminium. At present, the principal technical problems associated with the welding of aluminium are:

- solidification cracks in the weld metal
- liquation cracks in the heat affected zone
- pore formation and growth
- strength reduction in the heat affected zone

Both solidification and liquation cracks are thought to be due in the main to the occurrence of intermetallic phases with a low-melting temperature at the grain boundaries. Alloys with a wide solidification range are the most susceptible to cracking. This means that it is the hardenable alloys, to which zinc or copper have been added, which are most susceptible to cracking. Some alloys also contain lead, thereby increasing the risk of cracking. Solidification cracks can be avoided by selecting silicon-
alloyed consumables. It has also been demonstrated that silicon-alloyed consumables reduce the risk of liquation cracks in hardenable Al-Mg-Si alloys, probably because the solidification temperature of the weld metal is lower than that of the parent metal and any cracks therefore have time to heal before stress is created across the joint. In the solid-solution strengthening alloys, mainly alloyed with magnesium, it is those with a low magnesium content that are the most susceptible to cracking. However, many alloys, in particular the non-hardenable ones, but also the hardenable magnesium-silicon alloys, have very good weldability.

Pores in aluminium welds are usually caused by hydrogen from moisture. There is a very great difference in the solubility of hydrogen between the molten and the solid state. So, when solidification of the weld metal occurs, there is large supersaturation of hydrogen. The hydrogen is then precipitated as pores. To keep the pore formation to a minimum, the hydrogen content must be minimised. All sources of hydrogen (i.e. the shielding gas, parent metal and consumables) must be closely controlled. Recent investigations (7) have shown that the material in the gas hoses has a major influence on the moisture content. Hoses made from PVC or rubber give off moisture in large quantities and must be flushed with gas for perhaps 10 minutes after they have been idle for some time. Hoses made from PE or PTFE have a much lower moisture pick-up and the time for flushing can consequently be reduced.

Higher heat input is another way to improve the situation, as it gives the hydrogen longer to move out of the weld pool. However, despite these actions, it is difficult completely to suppress pore formation.

The reduction in strength around a weld in aluminium alloys is inevitable, except for alloys in the untreated or room-temperature-aged condition. This loss of strength is due to recovery and recrystallisation in deformation-hardened alloys and precipitation coarsening and dissolution in age-hardened alloys. To compensate for the strength reduction, several strategies are used. Most frequently, welds are placed in low stress areas. Other methods include locally increasing the thickness of material. Heat-treatable alloys can, in principle, be given renewed heat treatment (solution treatment and ageing) to restore these properties, but this approach naturally involves many practical difficulties.

Aluminium is almost exclusively welded using MIG or TIG. There is a wide range of consumables for welding aluminium, either pure aluminium or solid solution-hardened alloys. The welding wires are mainly alloyed with magnesium or, in the case of certain alloys, silicon. Modifications to the Al-Mg-system are made by adding manganese in varying amounts, to increase the strength still further.

The addition of titanium or zirconium, to act as grain refiners, is also quite common. However, the development of new alloys for welding wires is relatively slow, probably reflecting the demand from the market.

Conclusions
The most important trends when it comes to materials development and which will challenge the development of consumables are:

- improved productivity for commonly used steels
- increased use of steel with improved properties
- new consumables with improved characteristics
- new consumables with improved high-temperature characteristics
- new consumables with improved corrosion properties
- the development of consumables with an even lower hydrogen content, but also an improved understanding of weld metal hydrogen cracking mechanisms

On the process side, the following trends are anticipated:

- high-productivity systems

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Johan Elvander, M. Sc. (Materials eng.) joined Esab AB in 1982 after graduating from The Royal Institute of Technology in Stockholm. He started as development engineer for stick electrodes and now holds a position as head of Research & Development, business area Consumables in Europe.
Close to 10 years of research and development are culminating in the first industrial product in the shape of the THOR ArcWeld production system, a system for the automatic programming of welding robots, integrating the entire process from the import of CAD data to the execution of robot programs.

During the past year, the R&D company AMROSE A/S in Odense in Denmark has been collaborating with Ib Andresen Industri A/S in Langeskov in Denmark in the EU project known as TOMATO. The aim of the project has been to transfer the advanced robot technology (developed by AMROSE in close collaboration with Odense Steel Shipyards Ltd.) to other metal industries.

The first working prototype of a robotic production system controlled by AMROSE technology was successfully built and installed at Odense Steel Shipyards Ltd. in 1994–95 and it is still being used in the daily production of ship assemblies.

The TOMATO project has focused on developing the user interface and adapting the technical functionalities in order to ensure that the system meets the demands imposed by companies in the metal industry for a flexible production system.

An internal demonstration of THOR ArcWeld at Ib Andresen Industri was scheduled for the end of 1998 and AMROSE will be ready to introduce the system to the rest of the industry during the first half of 1999.

The robot works continually

The joint venture between the two companies in the TOMATO project has resulted in the identification of a series of technical success criteria for the introduction of THOR ArcWeld at a manufacturing company.

The immediate advantage of off-line programming is that the robot can keep working, while the programming is handled on office computers.

With CAD data as the starting point, it is possible to generate a geometrical model of a work cell and workpiece. Subsequently, a collision-free trajectory is calculated for the welding robot in in-
Integration with the workpiece manipulator.

The fact that the programming itself does not demand valuable on-line time makes the robot-welding of small series profitable. Using sensory equipment, real-time corrections can be made to the welding process, thereby ensuring high weld quality which in turn reduces the post-processing time.

Finally, costs are minimized for expensive precision fixtures which are only made to compensate for the traditional inability of robots to compensate for the incorrect position of the weld groove.

**Customer’s own system**

The system has been developed with a view to incorporating it in the customer’s daily production flow; from the construction department to the shop floor.

It is important that the system requires as little individual adaptation as possible—which is also the case when it comes to the interface with the customer’s CAD and robot systems. The customer must be able to continue using his own CAD system for the design of the workpieces which are going to be welded. At the same time, THOR ArcWeld generates robot programs directly for the robot system, which the customer then uses in production.

The program is modular in design and has an internal language for application development which ensures very simple adaptation to different customers and applications. The system is designed in such a way that it can work with workpiece models from 90% of all “mid-range” CAD systems. In the same way, the system makes it possible to generate robot programs for different robot controllers (e.g. MOTOMAN, CONOSS and HIROBO).

**Joint, seam and run**

THOR ArcWeld covers the entire cycle of operations for a workpiece — from 3D CAD drawings (which are imported into the system) to complete robot programs which are executed through a system-integrated computer on the shop floor. THOR ArcWeld also contains instructions for the robot operator to mount workpiece parts during the production process, for example.

In THOR ArcWeld, any given weld is split up into its individual elements: joint, seam and run.

Using these elements ensures the greatest possible control of the automation process. This results in maximum flexibility in the adjustment of welding requirements to different workpiece types. From heavy workpieces, such as a car lifting platform, which demand weld seams with high durability, to workpieces, such as industrial mixers, which demand visually high weld quality. Using the CAD model as the starting point, THOR ArcWeld automatically identifies the following three basic elements of the welds:

- Joints between plates
- Seams which are placed on the joints
- Runs which make up the seams

The automatic process which takes the workpiece from one step to another is based on customer-defined rules which can subsequently be modified and adapted as required.

Between each step of the automatic process, it is possible manually to adjust data and thereby deviate from the set rules.

The user operates in a graphical environment which displays the workpiece, the robot and the work cell, plus any positioners and fixtures. The user can continuously monitor the automatic process in the graphical window and is able at all times to intervene with data adjustments.

**The real world**

On the basis of actual working procedures at IAI, the following case illustrates the facilities of THOR ArcWeld.

The company receives an order for a number of items. Each item consists of both robot-welded plates and plates which must be bent before being welded onto the already welded parts of the item.

The construction department draws the particular workpiece in a 3D CAD program, whereafter geometrical data is imported into THOR ArcWeld.

The CAD model is enriched by welding data which is independent from the place and method of production (i.e. whether the workpiece is welded manually or by a robot).

A so-called assembly tree is built. The assembly tree specifies the order of assembly for the various parts of the workpiece. The user specifies joints between plates; seams and runs are then generated automatically.

The interaction of THOR...
ArcWeld with a customer-adapted process database may have specified that outer corner joints should be welded vertically, if possible. From this information, the program calculates how the positioner must move the workpiece between welding jobs with respect to the overall welding process.

Anchor points are specified. These must be taken into account before the welding process is initiated. The anchor points are subsequently converted into robot-controlled sensings.

It is possible to enter notes which can be read on the shop floor. An example of this is a note specifying that one in every ten of a certain type of weld must undergo quality control. This message will then appear on the computer screen on the shop floor after every tenth execution of the welding program.

Further work with the workpiece is then transferred to the robot programmer.

The workcell in which the workpiece is going to be welded is then chosen. Apart from a robot and its environment, the workcell also consists of a manipulator and a fixture.

A task tree must be set up. As opposed to the assembly tree, the job graph reflects the order and type of tasks to be executed on the workpiece on the shop floor. The jobs which make up the job graph are very varied: from robot welding and sensing to messages to the work-cell operator about the placement of workpiece parts and performing quality control.

In principle, THOR ArcWeld can automatically translate the list of weld seams into a complete robot program, but, in reality, some manual adjustment of the automatically generated data is required.

When the robot programmer is satisfied, he releases the program. The workcell operator can now download the program to the robot controller.

Before the robot is activated, it is possible to play back the simulation and thereby obtain a comprehensive view of the entire process.

The workpiece is mounted as specified on the computer screen and the robot program is started.

There is direct interaction between the system and the robot during the entire production process.

The robot operator monitors the messages on his screen and the robot automatically stops when a new workpiece part needs to be placed in the positioner. The robot does not start again until it is actively re-started.

Later versions will include a report tool in which various statistical data, such as the number of workpieces and welded metres, the welding speed and the number of stops, will be collected and presented in a report.

The maths inside
A non-traditional mathematical approach, combined with inspiration from the latest research results in the field of Artificial Potential methods, led the AMROSE team to create a new and highly-efficient robotics concept.

This new robotics concept includes mathematical techniques from the field of molecular dynamics. In this case, mathematical models enable the computation of the motion of atoms and molecules under the influence of attractive and repulsive forces.

Tweaking the formalism a little, the scientists turned the forces acting between atoms in nature into artificial forces, in a computer model which actively control the movements of robots.

The artificial forces are chosen to encourage the robot to move towards its target area and perform its task (e.g. weld), while at the same time avoiding collisions between the robot, the workpiece and the surroundings. The attractive forces can be visualised as rubber bands that drag the robot towards its goal. In the same way, the repulsive forces can be seen as springs that push the robot away from obstacles in the environment.

Artificial forces are not fully adequate when high-precision control over the robot tool is needed. In the THOR motion computations, the tool centre point is tied to a frame of reference that moves according to the specifications of the task. In this way, the tool is dragged along by the moving frame with the exact required (high-precision) motion.

Principles from molecular dynamics are used to generate robot motion.

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Charlotte Hybschmann Jacobsen has a masters degree in molecular biology. She is in charge of user interface design and documentation of the AMROSE products.

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Welding duplex chemical tankers
the ESAB way

Wide scale application of ESAB welding solutions at Factorías Vulcano S.A., Spain

By Ben Altemühl, Svetsaren editor, interviewing Factorías Vulcano production management.

Factorías Vulcano S.A., Vigo, is a medium size shipyard in the north of Spain producing an extensive range of civil and maritime products, including chemical carriers in both carbon and duplex stainless steel. Currently, the yard is finalising the construction of The Primo, a duplex chemical tanker for the Swedish shipping company Initiia. The fabrication, from the indoor panel lines down to the final outdoor block assembly, is characterised by wide scale use of ESAB welding solutions with a key role for ESAB OK Tubrod cored wires. This article reviews the production of chemical tankers at Vulcano. Special attention is focussed on the role of FCAW.

Introduction

The title “Welding duplex chemical tankers the Esab way”, is perhaps a bit over-ambitious, but it is rightly chosen in the sense that Factorías Vulcano apply our welding solutions in practically every stage of the fabrication process of chemical tankers. The shipyard has made intelligent use of ESAB’s capability to serve as a total supplier for stainless steel fabrication, selecting dependable and productive consumable/equipment combinations for practically all fabrication steps. The yard possesses a high level of practical welding knowledge, providing a solid basis for, sometimes difficult, but often fruitful technical discussions between our companies. Over the years, the cooperation in developing and implementing new techniques has developed such that today we feel we can rightfully claim that Esab’s mission statement to be “the preferred partner for welding and cutting” is fully valid for this shipyard.

Factorías Vulcano

Starting out with the repair of railway engines in 1919, Factorías Vulcano widened their capabilities to what they are today; a full scale fabricator of civil and maritime constructions. Today’s product range comprises civil engineering products like boilers, marine fresh water generators, refuse incinerators and sewage treatment plants, whereas the shipbuilding segment fabricates container ships, refrigerated vessels and chemical carriers.

Acknowledgement

We would like to thank Factorías Vulcano for their excellent cooperation in preparing this article. A special word of thank we address to Ramón Pérez Vázquez, Production Manager, Jesús Fernández Iglesias, Steel Supply Manager, and Javier Pérez, Welder Foreman. Their openness has contributed greatly to this article. In addition, we compliment our spanish Esab colleagues José Luis Sastre, Carmen Herrero and José María Fernández Vidal on the great marketing success achieved at Factorías Vulcano.
In 1990 the company commenced a three year plan to restructure and modernise the shipyard, involving a 1200M Pesetas investment. What results today is a modern medium-size shipyard with advanced FORAN CAD/CAM design facilities, an ESAB NUMOREX NXB9000 under water plasma cutting installation connected to the CAD/CAM system. Also, a panel fabrication line with two ESAB A6-LAE1250-TAC1000 submerged arc welding machines, mechanised welding stations for stiffener attachment and various systems for mechanised SAW and FCAW applied in sub-assembly and final assembly. The yard layout guarantees an efficient flow of work through production. Along with the modernisation, the yard implemented the ISO 9001 quality assurance system. Together with an orderbook of specialised projects that reaches well into the next century, the yard is well positioned to compete in today’s demanding market.

**Construction of chemical tankers at Factorías Vulcano**

Although fabricated out of two completely different base materials, carbon steel and duplex stainless steel, the construction of chemical tankers at Factorías Vulcano takes place according to established, modern shipbuilding practices involving panel fabrication, the construction of sub-sections, the assembly of block sections, and the final connecting of block sections in the dock. We shall focus on the role of duplex stainless steel coated wires. Since these are applied primarily in the dock assembly, we describe the fabrication of The Primo in reversed order.

Figure 1 gives a schematic view of a 16000DWT chemical carrier frequently built by Vulcano, and very much resembling the Primo. The vessel has 12 tanks in duplex stainless steel and two small tanks serving for storage of cleaning waste. Parts in duplex stainless steel are highlighted in red. Vertical assembly welds are indicated with yellow dots.

Figure 2 shows the Primo somewhere halfway during the assembly of the chemical cargo tanks. Prefabricated sections are highlighted with individual colours and all assembly welds are visualised by yellow lines, numbered 1 to 9, and described in the margin.

For a good understanding of the construction, we recommend to first have a look at Figure 4. It shows the next block section to be assembled, comprising a deck section and tank assembly, the corrugated bulkheads. As such, it will be turned and placed in the construction. The yellow lines in Figure 2 may, therefore, indicate ready welds or welds to be made when the next block section has been positioned.

The first step in the duplex stainless steel assembly work involves the joints numbered 1, connecting the prefabricated deck plates to construct the tank floor. Here Factorías Vulcano apply a combination of manual FCAW on ceramic backing strip for single sided root passes and SAW for the filling layers. ESAB OK Tubrod 14.37 has been selected as the FCAW consumable, because of its capabilities for downhand work. With its slow freezing, fluid slag, it is designed to weld at high travel speed giving high productivity (Figure 3). It gives good penetration and, after slag removal, the back side of the root requires no grinding or brushing. The ceramic backing strips to be used with this product require a rectangular groove to accommodate the slag and to promote a good bead appearance.

OK 14.37 is welded in 85%Ar/15%CO2 gas protection, a mixture applied at Factorías Vulcano for all FCAW (stainless and carbon steel). Here, and for all other FCAW, the yard uses simplistic rectifiers without the need for pulsing.

SAW filling is done with the ESAB wire/flUX combination OK 16.86/OK Flux 10.93, a combination widely applied in duplex stainless steel fabrication, and with an excellent reputation. The flux is a low-hydrogen, non-alloying, basic agglomerated type (AWS: SA AF 2 DC). OK Autrod 16.86 is of the 23Cr-9Ni-3Mo type alloyed with 0.15%N to obtain a weld metal with sufficiently overmatching mechanical properties, a good austenite/ferrite balance, and excellent corrosion resistance when welding standard UNS 92...
S31803 types of duplex stainless steel. Vulcano use ESAB A2 Multitrac SAW machines, guided by rails attached parallel to the joints. The same machine-consumable solution is used all over the yard, providing a dependable welding method in many production steps (see later).

The same method as described for the tank floors is used for the connection of the tank floor to the carbon steel hull of the bottom (2), be it with 309L type welding consumables. The flux-cored wire for welding the root pass on ceramic strip is OK Tubrod 14.22, also a rutile type for all positional use, whereas the wire/flux combination applied for filling is OK Autrod 16.53/OK Flux 10.93.

The next assembly step involves the placement of the two side wall sections to the bottom of the vessel where first the carbon steel parts are connected, followed by weld type number 3 between subsequent block sections. Basically, this is the same type of joint as between the corrugated bulkheads (6), but welded with a slight angle. It is a V-joint welded vertically-up, manually or mechanised with rail-track equipment, with OK Tubrod 14.27. This rutile cored wire with fast freezing slag system is by far the most productive solution for making these kinds of assembly welds, with deposition rates that reach up to 3kg/h. Single-sided root passes are again made on ceramic backing strips with a rectangular groove.

Assembly welds type 4 and 5 connect the tank walls to the tank floor. Both types are treated as semi-positional welds, primarily performed with FCAW. Root passes are welded on rectangular ceramic strips in the case of weld 4 and on cylindrical ceramics in the case of weld 5. The back side of weld 5 has poor accessibility due to the geometry of the construction. SMAW with ESAB OK 67.50, an established acid-rutile electrode for standard duplex grades, was found to provide the most practical and secure solution for sealing the root.

The next fabrication step concerns the placement of the third prefabricated block section comprising a deck section and a cross of longitudinal and transverse tank walls; the corrugated bulkheads. This section can be seen isolated, and upside down, in Figure 4. The prefabrication of this component will be described later.

After turning and positioning this section between the side walls of the ship, a number of assembly welds remain to be made.

Assembly welds type number 6 are the ones indicated with yellow dots in figure 1. They connect the corrugated longitudinal bulkhead with the previous tank section, and the transverse bulkheads with the corrugated parts attached perpendicular to the side walls. The welding method and consumable used are exactly the same as described for weld type number 3 (OK Tubrod 14.27), but the welding position is truly vertical-up.

To obtain optimal welding economy, Factorias Vulcano apply mechanised welding with rail track systems for the filler layers. Figure 5 shows a typical example of a vertical assembly weld made in this way. Deposition rates amount to 3kg/h when calculated at 100% duty cycle, which is highly productive for this kind of unavoidable assembly welds.

Assembly weld 7, between corrugated bulkheads and the tank floor, is carried out manually, because the geometry of the joint is too complicated to allow mechanisation (Figure 6). Moreover, the root gap may show misalignments, requiring the welder to manually build-up the root with a varying number of beads. OK Tubrod 14.27 proves to be a versatile and dependable consumable for this kind of demanding work. Root passes are made almost twice as fast as with stick electrodes, using cylindrical ceramic backing, with excellent ability to compensate for misalignment of the joint.
Connection between corrugated bulkheads and tank floor

Position: PC/2G
Root: FCAW with OK Tubrod 14.27, manually welded onto cylindric ceramic backing.
Filling: FCAW with OK Tubrod 14.27, manually.

Connection between corrugated bulkheads and between tank side walls

Position: PF/3G
Root: FCAW with OK Tubrod 14.27, welded manually onto ceramic backing strip.
Filling: FCAW with OK Tubrod 14.27, welded manually.

Tank floor from pre-fabricated plates.

Position: PA/1G
Root & 1st pass: FCAW with OK Tubrod 14.37, welded manually onto ceramic backing strip.
Filling: SAW with OK Autrod 16.86/OK Flux 10.93

Connection between vertical tank wall and angled side wall

Position: PC/2G
Root: FCAW with OK Tubrod 14.27, welded manually onto ceramic backing strip.
Filling: FCAW with OK Tubrod 14.27, welded manually.

Connection between angled side wall and tank floor

Position: PC/2G
Multi-layer T-joint; full penetration.
FCAW with OK Tubrod 14.27, manually.
Sealing: SMAW with OK67.50

Connection between tank floor and carbon steel hull

Position: PA/1G
Root & 1st pass: FCAW with OK Tubrod 14.22, welded manually onto ceramic backing strip.
Filling: SAW with OK Autrod 16.53/OK Flux 10.93

Connection between vertical tank wall and angled side wall

Position: PC/2G
Root: FCAW with OK Tubrod 14.27, manually welded onto cylindric ceramic backing.
Filling: FCAW with OK Tubrod 14.27, welded manually.

Figure 2: Principal dock assembly welds in d
Connection between corrugated bulkheads and tank cover

Position: PC/2G
Root: FCAW with OK Tubrod 14.27, manually welded onto cylindric ceramic backing.
Filling: FCAW with OK Tubrod 14.27, welded manually.

Connection between tank cover and between tank covers and side walls

Position: PA/1G
Root & 1st pass: FCAW with OK Tubrod 14.37, manually welded onto ceramic backing strip.
Filling: FCAW with OK Tubrod 14.37

Assembly weld 8, connecting a small, extending part of the corrugated bulkhead to the deck of the subsequent tank section, is done in a semi-overhead position with exactly the same welding procedure. OK Tubrod 14.27 is one of the best cored wires available for overhead work, because the stiff, fast freezing slag prevents sagging of the weld metal.

The last step in the assembly process involves the connection of the tank cover (weld type 9). This is done in the downhand position with OK Tubrod 14.37 (root passes on rectangular ceramic backing strips).

Subassembly

Going back to Figure 4, it can be seen that this prefabricated block section consists of two major parts; the tank cover and a cross of two corrugated bulkheads placed perpendicular to the tank cover.

Starting with the tank top, it is clear that it is composed of a great number of plates. The small yellow lines represent welds made indoor on the panel lines (described later) to form the panels out of which the deck is composed. The thick yellow lines are the pre-assembly welds connecting the panels to form the tank cover. They are made according to exactly the same welding procedure as described for the tank floor in Figure 2 (weld type 1). FCAW is used for the root and first pass (OK Tubrod 14.37 on rectangular ceramic backing strip) and SAW (OK Autrod 16.86/OK Flux 10.93) is used for filling and capping.

The sketch of Figure 7 describes the basic component of the corrugated bulkheads. As such, they are supplied by the steel fabricator, bent to the right geometry with welds connecting the three areas of increasing plate thickness. To form a complete longitudinal bulkhead nine welds are required. Figure 8 shows the fabrication of these welds. Again the combination of OK Tubrod 14.37 on ceramic backing for the root pass and OK Autrod 16.86/OK Flux 10.93 is applied for the filling layers.

Two pre-assembly welds remain to form the block section. The transverse corrugated bulkheads are connected to the longitudinal ones by means of K-joints welded mechanised in vertical-up
position with OK Tubrod 14.27 using cylindrical ceramic backing to allow fast root pass deposition. The cross of bulkheads created in this way is attached to the tank cover in PB position with OK Tubrod 14.27 using the same welding procedure as applied in the dock assembly for weld type 7.

**Panel fabrication**

Panel fabrication is carried out indoors on a panel fabrication line with two ESAB A6-LAE1250-TAC1000 submerged arc welding machines. Panels for the tank floor, the tank cover and for the side walls of the tanks are all prefabricated according to the same welding procedure. The number of plates comprising a panel varies. At the moment of our visit, there was no duplex fabrication in progress, so we describe the welding procedure by means of the sketch in figure 9a. Duplex plates are bevelled to a Y-joint with a land of 4mm and positioned on the panel line with a minimal root gap. To avoid contamination of the duplex material, AISI 316L plates are placed between the duplex plates and the carbon steel rollers of the panel line. SAW with OK Autrod 16.86 and OK Flux 10.93 is applied for the complete joint. The first layer is carried out with a tandem system; the two filling layers with single-wire SAW. After completing the above, the panels are turned and sealed with single wire SAW. At this moment, Factorias Vulcano are experimenting with a new ESAB solution aiming at single-sided welding of the panels, which would provide a substantial time saving. Successful tests have been carried out with a backing rail filled with fine grain OK Flux 10.93 enabling to deposit a good quality root pass that requires no sealing (Figure 9b). Application of this system, however, requires an investment in stainless steel rollers, because it does not allow protection of the duplex material in the way utilised presently. The feasibility study has not yet been completed.

**Steel grade and mechanical properties**

All duplex stainless steel used for the construction of the Primo is purchased from Avesta under the brand name Avesta 2205. It is a standard, molybdenum alloyed grade.

Mechanical properties of the welds are overlapping with all
Figure 8: Welding of a corrugated bulkhead. Root (below) made with FCAW; filling and capping with SAW.

ESAB consumables used for this project. The Ferrite number of the weld is required to be between 25–70 which is a normal requirement for duplex stainless steel welding, and sufficiently wide for construction practice.

The Ferrite number is checked by means of a representative sequence of weld samples in various stages of the construction, using the same welding procedure and consumables as for the actual welds. From the same samples, confirmation of mechanical properties are obtained.

Preheating is not applied, although a minimal temperature of 16ºC is prescribed; sufficient to avoid condensation under the mild climatic conditions of the region. The interpass temperature is limited to a maximum of 150ºC.

Appendix I shows a full WPS for OK Tubrod 14.27 prescribing the manual or mechanised assembly welding in PF position, as described in Figure 2 (weld type 6). It contains useful information for readers that have become interested in this product, as well as a free lesson in welding terminology in the rich and beautiful Spanish language.

To conclude

When having the privilege of visiting this modern, yet cozy shipyard in Galicia, I fell at home from the start, enjoying the warm and open atmosphere I encountered. It was very rewarding to see that Esab’s commitment to be a total supplier works out so well at Factorías Vulcano, and that our products are being applied to the full satisfaction of the yard.

To avoid leaving behind the impression that it is fun to be an editor for Svetsaren, I will refrain from describing the short boat trip across a beautiful bay, after the interview, to the small family restaurant where I received valuable lessons in seafood dining. “Disfrutaba de toda forma y un día regresaré”.

Figure 9a: Double sided SAW panel fabrication.

Figure 9b: Single-sided SAW panel fabrication. Root pass on gutter filled with fine grain OK FLUX 10.93
To meet the demands of the power generating industry with its aim of increasing steam temperatures and pressures, the development of more creep-resistant ferritic steels started in the mid-1970s. Ferritic steels were preferred to austenitic steels because of their lower coefficient of thermal expansion and their higher resistance to thermal shock (1). Of these steels, the modified 9%Cr 1%Mo steel known as P91/T91 or, in Europe, as X10CrMoVNb9-1, has been used in a wide range of industrial applications. As Table 1 shows, the room-temperature strength of the modified variant is superior to that of the conventional variant.

In addition to improved room-temperature tensile strength, the modified variant also has increased creep strength, lower ductile-to-brittle transition temperatures and higher upper-shelf energy. The improved mechanical properties are explained by small differences in the chemical composition consisting of controlled amounts of Nb, N and V in the P91 steels, see Table 2.

P91 is generally used in steam piping, headers and super heater piping where the advantages over conventional CrMo steels can be used either for weight reductions or to permit an increase in operating temperature. Arav and van Wortel (2) made a comparison of the pipe-wall thickness required for different creep-resistant materials in certain operating conditions and demonstrated that the wall thickness can be reduced by three-quarters if P91 is chosen instead of 2 1/4Cr1Mo steel (Figure 1).

Welding is one of the most essential fabrication processes for component manufacture. The weldability of P91 steels is very good. Due to the high alloying content, a relatively high preheating temperature (200-350°C) must be used. The exact choice of preheating temperature also depends on the material thickness and the amount of restraint. A low hydrogen content is naturally necessary and only the basic type of consumables should therefore be used.

When designing a welded component, it is important to consider not only the mechanical properties of the base material but in particular the strength and properties of the weldments. For components designed for high-temperature service, the creep properties must be regarded as central.

### Table 1. Mechanical properties of modified and conventional 9Cr-1Mo steel.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>$R_p$ (MPa)</th>
<th>$R_m$ (MPa)</th>
<th>$A_5$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional 9Cr-1Mo (P9)</td>
<td>min 205</td>
<td>min 415</td>
<td>min 30</td>
</tr>
<tr>
<td>X10CrMoVNb9-1 (P91)</td>
<td>min 415</td>
<td>min 585</td>
<td>min 20</td>
</tr>
</tbody>
</table>

### Table 2. The specified chemical composition of conventional 9Cr-1Mo (denoted P9) compared with the composition of P91 (X10CrMoVNb9-1). (wt%).

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Nb</th>
<th>V</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>P9</td>
<td>max 0.25- 0.30- max</td>
<td>max 8.0- 0.9-</td>
<td>0.15</td>
<td>1.00</td>
<td>0.60</td>
<td>0.025</td>
<td>0.025</td>
<td>10.0</td>
<td>1.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P91</td>
<td>0.08- 0.20- 0.30- max</td>
<td>max 8.0- 0.85- max 0.06- 0.18- max 0.03- 0.12</td>
<td>0.50</td>
<td>0.60</td>
<td>0.02</td>
<td>0.01</td>
<td>9.5</td>
<td>1.05</td>
<td>0.40</td>
<td>0.10</td>
<td>0.25</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of the wall thickness required for different creep-resistant materials. Assumed operating conditions 250 bar and 600°C. Note the large reduction in wall thickness which is possible when P91 steel is chosen. From Arav and van Wortel (2).
As a result, this paper will discuss the creep properties of weldments in P91 steels and the way they are affected by the welding procedure, post-weld heat treatment and consumable composition. There is also a brief discussion of the impact strength of P91 type weld metals.

**Weldment creep properties**

Several investigations have shown that, when creep tests are conducted across a welded joint in X10CrMoVNb9-1, creep fracture occurs mainly in the heat affected zone (HAZ) and only rarely in the weld metal. A soft zone that forms at the outer region of the HAZ, the so called Type IV zone (this denomination is based on a weldment cracking mode model made by Shuller et al. (3)), is a matter of great concern. In this zone, the temperature has not been high enough to return the alloy carbides into solution. Instead, carbide coarsening takes place and this minimises the precipitation strengthening (4). The effect is apparent as a hardness minimum. Figure 2 shows the typical hardness profile of a weldment in modified 9Cr-1Mo steel (5).

![Figure 2. Typical hardness profile of a weldment in modified 9Cr-1Mo steel (after reference (5)). Note the hardness minimum appearing in the outer part of the HAZ. WM=weld metal; C=coarse grain zone; F=fine grain zone.](image)

In addition, the temperature in this zone is just enough to austenitise the material, but it is not high enough to cause any significant grain growth. So, considerable grain refinement will contribute still further to reducing the high-temperature creep strength.

The reduction in creep strength due to this creep weak zone has been examined in several investigations. Creep strength reductions of approximately 20-30% have been reported (1), (2), (7). A recent investigation at TNO (6), using isostress creep tests, i.e. creep testing at constant stress with varying temperature, demonstrated creep rupture lifetimes almost one order of magnitude lower for weldments compared with parent material (Figure 3).

The creep-weak zone is very narrow. The limited width of the zone leads to macroscopically low ductility in the type IV fractures. Figure 4 illustrates the differences in the elongation of base material and cross-weld specimens as obtained by TNO (6).

As so many of the creep properties of weldments are controlled by this creep-weak zone, it is relevant to ask whether this zone can be removed or made less harmful in some way. The remaining part of this section will deal with the influence of the welding process, the post-weld heat treatment and the composition of the welding consumable.

Provided that fusion welding is employed, the Type IV zone will always be present, irrespective of welding process. It is inevitable that there always will be a zone that is exposed to the critical temperature range. The width and the distance of this zone from the fusion boundary may, however, vary. In this case, the welding process will only have an indirect influence, through the heat input and the cooling rate. A higher heat input will lead to a wider zone, which will be placed further away from the fusion line. Recent investigations indicate that a wider zone is more detrimental to creep properties than a thinner one. So, very high heat...
inputs should be avoided when welding P91 steels. However, as yet it is not possible to specify an upper limit for the heat input.

A typical post-weld heat treatment temperature for P91 steel is 750–760°C. As can be understood from the mechanism that causes the soft zone, post-weld heat treatment in this region does not “cure” the loss of creep strength.

A couple of unconventional pre- or post-weld heat treatment routines have been proposed, but none has yet proved to be useful for industrial applications. From the discussion of Type IV cracking in the preceding paragraph, it might be thought, when the subject is examined from a creep point of view, that the chemical composition of the weld metal is of less interest. This is, however, not the case. The chemical composition affects the creep strength of the weld metal and, because of the stress redistribution mechanisms that are activated in a creep-loaded weld, the creep lifetime of the Type IV zone is also affected. Too strong a weld metal will lead to a concentration of creep strain in the weakest area, i.e. the Type IV zone. Moreover, when deformed, a weld metal that is weaker than the parent metal will attempt to shed load onto the adjacent region and thereby induce a Type IV failure. So, the optimum solution is probably to aim at weld metal creep strength in the same range as that of the parent material.

The Nb, V and N content of the consumables has been shown to be important for the weld metal creep properties, just as it is for the creep properties of the parent metal. The role of these elements is the same, namely to form and stabilise carbides and nitrides. The importance of the three elements is clearly shown in Figure 5 which is a comparison between an electrode of standard OK 76.98 composition and an experimental electrode (8). The standard electrode shows clearly better creep strength than the experimental one, which is leaner in its composition.

<table>
<thead>
<tr>
<th></th>
<th>Nb (wt%)</th>
<th>V (wt%)</th>
<th>N (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK 76.98</td>
<td>0.056</td>
<td>0.197</td>
<td>0.051</td>
</tr>
<tr>
<td>experimental</td>
<td>0.020</td>
<td>0.142</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Figure 5. Creep strength of cross-weld specimen welded with different consumables. This illustrates the importance of having the correct amount of microalloying elements.

**Weld metal toughness**

The weld metal toughness may be thought to be irrelevant in assemblies designed for operation in the temperature range of 500-600°C, since this is definitely far in excess of the temperature range at which brittle fracture could occur. However, the components may very well also be stressed at ambient temperature during testing or start-up, for ex-
Table 3. Mechanical properties of OK 76.98 and OK Tigrod 13.38. Typical values.

<table>
<thead>
<tr>
<th>Product</th>
<th>R_p0.2 (MPa)</th>
<th>R_m (MPa)</th>
<th>A_%</th>
<th>KV (J) at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK 76.98</td>
<td>650</td>
<td>760</td>
<td>18</td>
<td>70</td>
</tr>
<tr>
<td>OK Tigrod 13.38</td>
<td>690</td>
<td>785</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>EN 1599 requirement</td>
<td>min 415</td>
<td>min 585</td>
<td>min 17</td>
<td>min. average 47</td>
</tr>
</tbody>
</table>

Table 4. Specified composition for OK 76.98 and OK Tigrod 13.38.

<table>
<thead>
<tr>
<th>Product</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK 76.98</td>
<td>0.08-0.2</td>
<td>0.4</td>
<td>max</td>
<td>8.0</td>
<td>0.4-0.85</td>
<td>0.15-0.04-0.030</td>
<td>0.13</td>
<td>0.5</td>
<td>1.0</td>
<td>0.02-0.02</td>
<td>10.0</td>
</tr>
<tr>
<td>OK Tigrod 13.38</td>
<td>0.08-0.20</td>
<td>0.35-</td>
<td>max</td>
<td>8.6</td>
<td>0.6-0.85</td>
<td>0.18-0.04-0.030</td>
<td>0.12</td>
<td>0.50</td>
<td>0.60</td>
<td>0.010-0.010</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Further development

There is strong environmental and economic pressure to increase the thermal efficiency of power stations still further, thereby leading to a steady increase in steam temperatures and pressures. Alloying with W, Cu and/or Ni has produced a range of new steel variants with even higher creep strength than X10CrMoVNb9-1. The effect of welding these materials has not yet been thoroughly investigated, but some results indicate that the effect is similar to that in X10CrMoVNb9-1.

References


About the authors

Eva-Lena Bergquist graduated from Bergskolan in Filipstad in Sweden in 1986. She spent the following ten years working primarily on failure analyses at SAAB Automobile and later at ABB STAL AB. In 1997, she joined Esab and is now a research engineer at the Central Laboratorium in Göteborg.
Since the beginning of the 1990s, laser welding has been an accepted method in the automotive industry for welding vehicle bodies and bodywork components. Volvo Cars opened the door for this technology when it began using lasers to weld the roof joints of the 850 model, currently the S70 and V70 model. The method has now become state of the art and a number of other large car manufacturers, like BMW, Mercedes, VW and Audi, now perform similar welding. However, the giants in the automotive industry are not the only ones who use laser welding.

The large-scale production of laser-welded components for vehicles has also developed. In the small town of Torsås in Småland in Sweden, AP Automotive System Torsmaskiner AB has been involved in the professional laser welding of catalytic converters for the automotive industry for the past five years.

AP Torsmaskiner AB, as the company is generally known, is one of the leading suppliers of manifolds and catalytic converters to the European automotive industry. The company’s product programme previously also included silencers. Major customers include Volvo, VW, Ford and Mitsubishi. Production is highly automated and, at the 1998/99 year-end, it included some 50 industrial robots for conventional welding.

Hans Nyström works as a project leader with project planning for new production and, at the same time, he is responsible for welding at AP Torsmaskiner AB. He was involved at the very start when laser welding was first introduced and he tells a fascinating story about the arrival of laser welding in Torsås.

He described the successful laser welding of catalytic converters for the automotive industry at a seminar for the Swedish laser group within Sweden’s Engineering Industries.

“It all began in the autumn of 1992,” says Hans Nyström. “It was decided that we would start producing what is known as a ‘stamped muffler’, patented by our owners AP Parts in Toledo in the USA. This silencer was designed for the Volvo 960.”

**Success vital**

“The ‘shell’ would be joined together using laser welding. This was a wonderful opportunity for us to introduce an entirely new welding method,” Hans continues. “The machine was to be a 6 kW CO₂ laser. Some capacity was left over on this machine and so we decided to laser weld the catalytic converters, because we had just received an order for a catalytic converter for the Volvo 850. No sooner said than done. We designed the first catalytic converter for laser welding.

Test welding was done at Permascand AB in Ljungaverk on their 1.5 kW CO₂ laser. The material in the catalytic converter was ferritic stainless W1.4512 and two plates, 1.5 mm thick, were going to be joined using lap joints.
One question which would have a decisive effect on future developments was the structure of the weld metal. We started to weld with argon as the shielding gas. It became clear that the weld depth was not sufficient. The results were improved when we changed to helium and the weld metal analysis was perfect! The catalytic converter project could continue.

**Laser welding cell from the USA**

The laser welding machine was built by LMI, a company just east of Minneapolis in the USA. The energy source in the machine is a Trumpf 6 kW turbolaser, but everything else was built by LMI. The equipment has three axes with two welding stations and the laser beam is switched from one station to the other via a moving, indexing mirror.

Hans Nyström goes on to explain that, in September 1993, a so-called run-off took place at LMI. At that time, the welded object was the silencer that was going to be produced for the Volvo 960. It consisted of six “shells” made of ferritic, stainless sheet steel which were put together—four were 0.5 mm and two 1.0 mm. In addition, two of them (0.5 mm) were aluminium-plated. It emerged that laser welding this material combination was not without its problems as large numbers of pores developed. The main reason for this was found to be a kind of dry oil which was used when the plates were pressed and which still remained in such quantities that it made laser welding impossible. This problem was eventually solved, however.

**Training is important**

“Training is an extremely important parameter,” Hans continues. “Two operators were selected for two weeks of training on this machine. One week was spent at our sister company in Granger in the USA, where a similar product was produced on similar machines. The other week was spent at LMI in connection with the so-called run-off. This subsequently proved to have a very important effect on our production when it came to the handling, maintenance and service of the equipment.

**Commissioning the catalytic converter — a total success**

“Just like the commissioning of any new machinery and equipment, the commissioning process of the shell silencer was associated with some problems,” Hans explains.

“Material problems with the silencer now emerged in the form of an excessive amount of the previously-mentioned dry oil which was left after pressing the plates. We have now sorted out this problem for the most part, but it recurred from time to time as production continued. Other problems of different kinds which resulted in stoppages were caused by the laser. Otherwise, everything functioned almost perfectly.”

So how did the commissioning process of the catalytic converter go? “It went fantastically well! All that was needed was a minor adjustment after the ‘starting shot’ was fired! “I have never been involved in such a smooth commissioning process,” Hans Nyström continues — and he has 30 years’ experience of production engineering. “Production and the system both functioned very well until a short time ago when we were forced to replace both the turbines in the laser. It had then been in operation for 17,000 hours.”

**Useful experience — money to be saved**

“Yes, we have certainly learned a great deal from this installation,” Hans Nyström adds. “In our view, the design of the cross-flow which keeps dirt and dust away from the focusing optic could be improved. We think that far more resources should be invested here.

“When it comes to the supply of shielding gas, there is scope for any number of new ideas,” Hans says. "It has become clear that the design of the gas nozzle is very important. Its position and the way the shielding gas is directed at the welding point are just as important. We have seen that this affects the gas flow, the welding speed and the weld quality. So there is money to be saved here.”

A precise fit, top-class cleanliness and consistent quality are vital in the material that is going to
be welded if the results are to be satisfactory.

**Stable fixtures — moderate force**

“Stable fixtures are essential for secure fixation. However, there are some limits when it comes to the gaps between the plates when lap joints are performed. Some care must be taken in terms of the tension in the plates. If the joints are too tight, pores will be produced as some gas forms between the plates. These pores can then form because these gases can only escape via the molten pool.

“So make sure the gap is one-to two-tenths of a millimetre wide!”

However, with smaller material thicknesses than those mentioned above, other rules may apply, according to Hans Nyström, as he concludes his presentation.

Hans Nyström’s description is an excellent example of the kind of things that can happen when a new technology like laser welding is introduced into production. It is essential to be in control of all the parameters, otherwise problems can occur. However, in the right conditions, laser welding is a highly productive and reliable welding method, the use of which is now increasing sharply in manufacturing industry.

Hans Nyström and his colleagues at AP Torsmaskiner AB in Torsås are now examining new applications for laser welding!

**About the author**

Hans Engström is acting Head of the Division of Materials Processing at Luleå University of Technology, Luleå, Sweden. He has been actively involved in the R&D of laser materials processing since 1981 and has worked in several areas, such as laser surface modification, systems and welding. For many years, he has also headed the laser group at the university. In addition, he had been actively involved in the successful introduction and progress of the Laser Group at the Association of Swedish Engineering Industries, as the editor of the group membership journal, Laser News.
For many years, there has been a desire to increase the use of high strength steels in different applications. Obviously, by increasing the strength of the steel, thinner, more economical solutions can be created. There are currently many examples of welded structures made from steels with a yield strength of up to 690 MPa. Although very thin plates are used in many cases in these constructions, resulting in a low risk of brittle fracture, there are also some large types of construction, such as submarines, in which thick plates are used.

In these heavy plate structures, the risk of brittle fracture has been assessed thoroughly, using conventional impact toughness testing, fracture mechanics testing and detonation tests. It is generally believed that a steel with higher strength also requires greater toughness, compared with a lower strength steel.

There are several lines of development which increase the need for new welding consumables with a strength level of 690 MPa and above. The first is the wider use of 690 MPa steels (1). For most applications, there is a requirement for weld metal strength which overmatches the strength of the base metal. For the 690 MPa grade of steel, there are few consumables which overmatch the strength of the steel, while still meeting the toughness requirements. Instead, matching weld metals are used. This has raised the question of the structural integrity of these joints, as it is thought that the weld metal has lower toughness than the steel. Research programs which are addressing this problem are currently in progress. In this context, a second line of development can also be seen. Apart from looking for overmatching weld metals, there is also a call from fabricators to use more high productivity processes for welding these steels, mainly cored wires and submerged arc welding. Some results of investigations in this field has been dealt with in this paper.

The second line of development is to enhance the yield strength to make it even higher than 690 MPa. Steels with a yield strength of 900, 1,000 and 1,100 MPa and good impact toughness are currently available on the market. The applications for these steels include mobile cranes, conveyor systems and roof supports. These steels are currently welded with undermatching consumables and the welds therefore have to be placed in low-stress sections. There is also a drive towards the use of heavy plates with these very high strengths. The need for higher strength consumables is then likely to increase.

In this paper, consumables producing weld metals with a yield strength of 690 MPa and above has been presented. The mechanical properties of different welding procedures has been given and the relationship between strength and impact toughness has been discussed. Firstly, however, a general presentation of the relationship between microstructure and mechanical properties will be made.

**Microstructure and mechanical properties**

In order to understand the relationship between microstructure and mechanical properties, some typical microstructures from weld metals with different yield strengths are shown in Figure 1. All the micrographs were taken in the last deposited bead, in order to avoid the influence of heat treatment from subsequently deposited beads. The microstructure in the last deposited bead is, however, generally only part of the total microstructure of a welded joint. When multipass welding is used, the weld metal contains a number of beads, each of which contains a number of subzones in which the weld metal has been reheated to different peak temperatures. This produces a complex pattern of zones which may have different properties. Furthermore, the welding procedure also influences the size and proportions of the various zones, as well as the microstructure within each zone.

So, the mechanical properties of different weld metals must be compared with great care. The microstructure, which is dependent on the chemical composition and cooling conditions, is just one factor which influences the mechanical properties. The welding procedure, including the number, size and placement of beads, is just as important. In the case of manual welding, the welder himself then can have a major influence.

Despite these difficulties, some general conclusions on the effect
of microstructure on mechanical properties can be drawn. In Figure 1a, the three most typical microstructural constituents are seen: allotriomorphic ferrite along the prior austenite grain boundaries, Widmanstätten side plates and acicular ferrite. The weld metal is of the basic type and therefore has a relatively low content of non-metallic inclusions. The percentage of the various constituents varies with the alloying content and cooling rate of the weld metal. As a very general rule of thumb, a weld metal with this type of appearance will have a yield strength (YS) of approximately 450–550 MPa and an ultimate tensile strength (UTS) of 600–700 MPa. The ductility, measured as A5, is about 25% and the area reduction at fracture (Z) is approximately 70%. All these values are just guidelines and will vary with the precise conditions in which the weld metal was deposited.

Two main mechanisms are available for strengthening a low-alloyed C-Mn weld metal: grain refinement and solid solution hardening. Particle dispersion hardening should be possible to apply in principle, but it generally leads to unacceptably low impact toughness. Grain refinement is achieved by making the alloy more hardenable, so that the transformations occur at a lower temperature. As a result, a larger amount of the fine-grained acicular ferrite can be formed. If the amount of alloying content is even higher, bainite or martensite is formed.

Acicular ferrite is the most problematic constituent to control. The exact mechanisms which are involved in the formation of this phase are still not understood.

Figure 1b shows a weld metal with a YS of approximately 690 MPa, a UTS of around 900 MPa, a ductility of 20% and a reduction in area of about 60%. This weld metal is alloyed with nickel, chromium and molybdenum, increasing the contribution by solid

Table 1. Summary of consumables for welding steels with a yield strength of 690 MPa or above.

<table>
<thead>
<tr>
<th>Product</th>
<th>Process</th>
<th>Chemical composition (%)</th>
<th>Mechanical properties</th>
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<td>Mn</td>
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<td>FCW</td>
<td>0.09</td>
<td>1.7</td>
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Figure 1 Micrographs illustrating the variation in the microstructure of weld metals with various strength levels
(a) a weld metal with a yield strength of 450–550 MPa containing allotriomorphic ferrite, Widmanstätten ferrite and acicular ferrite
(b) a weld metal with a yield strength of 690 MPa, with a mixture of acicular ferrite, bainite and martensite in the microstructure
(c) a weld metal with a yield strength of around 900 MPa, with a microstructure consisting of a mixture of bainite and martensite.
solution hardening to strength. For the most part, however, strength is increased by an increase in the proportion of low-temperature transformation phases. The allotriomorphic ferrite along the prior austenite grain boundaries has essentially vanished, as has the Widmanstätten ferrite. The microstructure now consists of a mixture of acicular ferrite, bainite and martensite.

Figure 1c shows a weld metal essentially comprising bainite and martensite, with a YS of 900 MPa, a UTS of about 1,000 MPa, a ductility of 18% and a reduction in area of around 55%.

These examples show that it is possible, at least to some extent, to connect mechanical properties to microstructure. However, there are some points that should be discussed in greater detail. The first is the tensile properties. They are generally measured with longitudinal tensile bars with a 10 mm gauge diameter. Normally, this means that many zones are sampled and the mechanical data are an average of the individual values in these zones. However, in certain situations, smaller size specimens are used, sampling fewer zones. In very special situations, depending on the exact welding procedure, more or less fully weld-normalised microstructures can be sampled, thereby producing far lower strength than if the full weld metal structure had been examined. This risk is particularly great for weld metals of lower strength. For higher strength welds, the difference in properties between the different zones diminishes, due to the higher hardenability of the alloys. This can be substantiated by the hardness variations from the face to the root through the three types of weld metal from Figure 1. This is shown in Figure 2. Needless to say, the weld metals have different hardnesses, but the variation in hardness along each line is more interesting. As can be seen, there is less scatter in the harder alloys, which means that there is less variation between different zones for these alloys. Consequently, they are less sensitive to tensile test specimen size.

The variation in hardness between different zones also has an effect on what is perhaps the most important property for weld metals, namely impact toughness. It is far more difficult to give a number to the impact toughness for the three types of alloy in Figure 1 than to the tensile properties, as the impact toughness is even more process dependent.

The factors which control impact toughness are difficult to present clearly and briefly. The basic microstructure naturally has a major influence as a result of grain size dependence: a finer grain size produces higher impact toughness. When lower temperature transformation products, such as bainite and martensite, appear on a larger scale in the process consumables

<table>
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<th>Process</th>
<th>Consumable</th>
<th>Heat input (kJ/mm)</th>
<th>Plate thickness (mm)</th>
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</table>

*) Tensile strength in transverse tensile test.

Table 2. Summary of some welding procedures using consumables for welding high strength steels. The results of the mechanical tests relate to the weld metal, unless otherwise stated.

Figure 2 Hardness development through the three weld metals in Figure 1. The difference in hardness reflects the difference in strength. The variation in hardness along the line of measurement reflects the sensitivity of each weld metal to the heat generated by subsequent passes.
microstructure, impact toughness is generally reduced. To obtain an acceptable impact toughness for these phases, other measures must be taken, such as using a very low carbon content. Increasing the addition of alloys to increase strength usually reduces impact toughness, with the exception of nickel, which tends to increase it. It is usually claimed that increased strength results in a reduction in impact toughness, but this depends on the mechanism that is responsible for the increase in strength. Impact toughness also depends on the size of non-metallic inclusions. This is determined by the basicity of the slag system (or oxygen potential of the gas) and the heat input.

Recently, the effect of minor elements on impact toughness has attracted a great deal of interest. There are also factors such as embrittling elements like nitrogen and the actual welding process also appears to have some influence. Processes with higher productivity may have a somewhat lower impact toughness. However, many details relating to the influence of the above factors associated with toughness have not been clarified.

Figure 3 Impact toughness at –40°C, measured at several positions across a welded joint. The plate on the left-hand side was wrought while the right-hand plate was cast.

Figure 4 Graph showing the relationship between yield strength and impact toughness for weld metals with a yield strength of more than 600 MPa. This illustrates that high impact toughness values can be obtained for high strength weld metals using several welding processes.
In very rough terms, it can be assumed that a weld metal like the one in Figure 1a has an impact toughness at –40°C of 150 J, the one in Figure 1b 100 J and the one in Figure 1c 50 J. Due to the greater homogeneity of the microstructure of the higher alloyed weld metals, they have far less scatter in terms of impact toughness.

**Welding steels with a yield strength of 690 MPa**

In this section, consumables for welding steels with a yield strength of 690 MPa will be presented. Some results from different welding procedures will also be shown.

Table 1 gives details of the Esab range of consumables for welding high strength steels. The chemical compositions and mechanical properties relate to all weld metal. It should be noted that the two last consumables are designed for welding steels of even higher strength.

A number of welding procedures in which these consumables have been used are presented in Table 2, together with the results of mechanical testing. As can be seen, the welding procedures span quite a large field, in terms of both heat input and plate thickness. A parameter which is not given in Table 2 but is still important is the preheating and interpass temperatures used during welding. A preheating temperature of 100–150°C was generally used for all thicknesses. This prevented hydrogen cracking. In the case of modern quenched and tempered steels with a low carbon content, the main risk when it comes to hydrogen cracking lies in the weld metal. So the choice of preheating temperature should not be based on the composition of the steel. Unfortunately, there are as yet no formulae or graphical methods that provide reliable guidelines for the avoidance of weld metal hydrogen cracking. In order to find suitable preheating temperatures, more elaborate methods, such as a Tekken test, should be used.

As can be seen from Table 2, high tensile strengths were found in the weld procedures. In general, when it came to the transverse tensile tests, fracture was found in the base material. However, there might be a problem in situations in which the consumables only give a slight overmatching to 690 MPa in an all weld metal test. The reason for this is that the weld metal, which is created by mixing the consumable and the base material under the influence of the cooling conditions dictated by the welding procedure, does not usually increase very much in strength, unless large amounts of alloying elements are picked up from the base material. The base material, which has a specified minimum yield strength of 690 MPa, has a much higher yield strength in practice. It is not uncommon for the steel to have a yield strength which is 100–150 MPa higher than the minimum specified value. Naturally, these steels also have a higher ultimate tensile strength. So, even with weld metals which should nominally overmatch the strength of the steel, fracture may take place in the weld metal in a transverse tensile test.

What is particularly encouraging when it comes to the welding procedures in Table 2 are the good values for impact toughness which were measured in the weld metals. Figure 3 shows a plot of the impact toughness at –40°C for various positions across a weldment in steels with a yield strength of 690 MPa. In this particular case, which relates to the FCAW procedure using PZ 6148, the welding was done between two plates, one rolled and one cast. As can be seen, there is a decrease in toughness from the base material via the HAZ to the weld metal. This picture is often found for welds in 690 MPa steels, irrespective of the consumable or welding procedure. The impact toughness of the weld metal is good, but it is slightly lower than in the HAZ.

A large number of test welds have been prepared in order to study the connection between the strength and impact toughness of weld metals. A summary of this connection is presented in Figure 4, which presents data for submerged arc, manual metal arc and flux cored arc weld metals. The yield strength of the weld metals varied from about 650 MPa to above 1,000 MPa. A clear trend can be seen — an increase in yield strength produces a decrease in impact toughness. As can also be seen, weld metals from manual metal arc welding have a slightly higher impact toughness than submerged arc weld metals.

**Conclusions**

Welding steels with a specified minimum yield strength of 690 MPa is possible using most of the common arc welding processes. There are high productivity processes for welding these steels, mainly cored wires and submerged arc welding. There is a range of consumables that will provide both the strength and impact toughness to match the base material properties. To avoid hydrogen cracking in the weld metal, a preheating temperature of 125–150°C should be used; the lower temperature is applicable for thin plates and a low level of restraint. One particular problem is the actual yield strength of the delivered base materials, which is often far higher than the specified minimum yield strength. The weld metals normally overmatch the steel, but, as the yield strength of the weld metal increases, a decrease in impact toughness is seen. This then indicates that a consumable with slight overmatching properties should be selected for each case.

**About the author**

Lars-Erik Svensson, PhD, is manager of the Esab Central Laboratories in Gothenburg. He has worked for more than 15 years with welding metallurgy, focusing primarily on unalloyed and low alloyed steels. He has published one book and more than 25 papers on the microstructure and properties of welds.
Cutting systems in an environmental context

by Dipl.-Ing. Klaus Decker, ESAB-HANCOCK GmbH, Karben, Germany

The most commonly used cutting technologies are shown in Figure 1. The cutting ranges for different materials and plate thicknesses are given, together with the recommended maximum thicknesses for the cutting processes and the energy level/amperes in question. In addition to this information, current usage largely depends on the accuracy that can be obtained and this is illustrated in Figure 2.

During the past 30 years, the environmental issues associated with thermal cutting have attracted steadily increasing attention. Around 1960, plasma cutting was virtually unknown and laser cutting had not been invented. Oxy-fuel cutting was triggering some degree of environmental discussion, mainly as a result of the very high Nx-Oy content found in connection with cutting. At this time, the industry in general took no special operator precautions against dust and fumes. The increased use of cutting as one of the means of optimising steel designs and, in particular, the increasing focus on operator comfort in general in Northern Europe during the years that followed virtually kicked off a new comfort business programme, based to a very large degree on the increasing awareness of the health hazards associated with dust, fumes and gases, noise, radiation and ergonomics in general.

Dust, fumes and gases

The first steps when it came to removing the health risks posed by dust, fumes and gases focused on oxy-fuel cutting and were based on national regulations, in particular those in Germany and Scandinavia. The result was the typical cutting table with fume extraction, divided into compartments, so that the position of the torch controls the compartment from which extraction is active (Fig. 3).

Over the years, this type of installation has been improved in terms of design and functionality and is now thought to deal very effectively with the environment inside current production facilities, provided that the upkeep...
and verification of the function is performed correctly.

This type of installation is used for oxy-fuel and dry-plasma cutting and the actual process determines the extraction volume to be used, the normal range being 4,000-8,000 m³/h for a compartment length of 500-1,000 mm and table widths of up to 4,000 mm.

Whereas the interior environment was catered for very effectively by these measures, the pollution from the extraction funnel into the surroundings was handled using a coarse separator and a traditional cyclone, in combination with a funnel height which was decided from case to case. Expressed in figures, this type of funnel extraction can typically accommodate a dust content in the region of 50 mg/m³ and upwards with an aerosol type of particle size, although the actual analysis depends on the type of material and the cutting process.

At the present time, this type of installation works satisfactorily in many environments. With increasing urbanisation, however, neighbourhood pollution is a growing problem. Special cyclones like that shown in Figure 3 and special filter systems (Fig. 4) can create solutions in which the airborne pollution from dust into the surroundings is 5 mg/m³ and less. There is no question that the call for these systems will increase, in particular when particles originate from the cutting of stainless types of material.

Dry-plasma cutting was referred to explicitly above as opposed to water-plasma cutting, a process which is far better in the environmental context than the dry-plasma process, as the cutting takes place with the plate and plasma jet under water, even though the energy input is relatively high. It is performed with special water tables with rapid operating level control. As regards dust, fumes and gases and even noise levels, water-plasma cutting is very advantageous. To put it bluntly, practically everything stays in the water and requires only something like a once-a-year clean-out of the residue from the bottom of the table, while the water can be disposed of as harmless through the regular sewage system.

The obvious process advantage, as seen from an environmental viewpoint, is accompanied by the advantages of high cutting speed and improved precision due to water cooling. Marking must, however, take place on the dry plate before cutting and the water level operations reduce productivity, in particular for small plate formats.

With regard to dust, fumes and gases, laser cutting by and large calls for environmental measures which are very similar to those described for oxy-fuel and dry-plasma cutting. The volume of hazardous gases and dust is, however, small, due to the cutting gases that are used and the very narrow kerf.

**Noise and radiation**

Whereas the previous paragraph concluded that many environmental problems have been solved, the situation is somewhat different when it comes to the noise and radiation problems associated with dry-plasma and laser cutting. In both cases, the practical and, at the same time, somewhat drastic solution appears to be to “encapsulate” the cutting installation from the surrounding environment, as well as from the operator. This is not as easy as it might look at first sight. Isolation during ongoing cutting excludes the traditional handling of plates and cut parts and will undoubtedly reduce productivity to some degree, even if large investments are made to facilitate these operations. The situation when it comes to handling under these circumstances represents a major future challenge for which the present state of the art in cutting systems is not fully prepared. This issue will be touched upon again in a subsequent paragraph.

To give just one example. In many cases, fine-beam plasma cutting is currently an alternative to laser cutting as illustrated by Figure 2. The typical noise level is around or above 100 dBA (distance of one metre). It is not especially practical to encapsulate the torch and beam, but it can be done and will reduce the noise level to below 85 dBA. The industry is, however, not particularly willing to accept such a solution as it will increase upkeep costs and generally make cutting more costly because the operator is unable to watch the cutting process and also because the effective cutting field for a given machine size is reduced.

One solution to the problem could be a separate building for the installation with remote operation facilities for the cutting operation and to some extent also for loading and unloading. This is
undoubtedly a very costly solution and one with reduced productivity.

Another solution could be to adapt the process to water-plasma operation. This would call for a water table, an air muffler around the torch and a larger cutting power source to provide the increased energy that is needed for under-water cutting. Also a solution which calls for high investments and has inherent features that will reduce productivity. To the knowledge of the author, none of the solutions has so far actually been put into operation.

**Ergonomics in general**

The development of controls for CNC cutting has brought about a general improvement in ergonomics. Just consider the following examples – marking equipment, automatic nesting, automatic cutting bridges, colour monitor facilities, automatic height control, flame control and monitoring by sensors and advanced programming facilities.

In the case of cutting installations, ergonomic improvements worth mentioning include automatic plate alignment, tables with transport facilities for the outloading of parts and double tables, roller bed arrangements, special overhead cranes, special arrangements for easy slag removal, all features that have helped to reduce the heavy physical work and the man-hours used per metre cut.

**Development targets**

Productivity in the broadest sense of the word is the driving force when it comes to selecting the development targets for the cutting process as applied in cutting installations. This focuses attention on the operations that are needed after cutting, as a result of a more or less perfect cutting performance. In plain terms, the answers to quality issues such as accuracy, freedom from dross, squareness and bevel quality.

In the case of different cutting processes, we find different combinations of answers to these quality issues.

At the present time, dross-free and accurately-cut parts are basically regarded as the major targets to aim for, because the cost associated with dross removal by post-processing cut parts is considerable, as is the lack of precision for welding operations that, more often than not, follows after cutting.

Another productivity issue which has a direct bearing on the nature of the cutting process is the minimising of process downtime due to wear to torch tips, electrodes and nozzles. Systems for monitoring, surveillance and fast and precise exchange modes are in demand for all processes.

It is also relevant to mention the constant design attention that must be paid to the interaction between the aforementioned development of controls and the corresponding electrical and mechanical design of cutting machines, as regards their dynamic response to rapid movements with up to five degrees of freedom. A very high degree of dynamic response is an absolute prerequisite for realising the potential advantages offered by any sophisticated cutting process.

Finally, modern IT developments, utilised correctly with advanced sensor technology, have made great advances in diagnostic systems possible. This trend will continue and lead to further improvements relating to preventive upkeep to minimise downtime, to secure fast troubleshooting and provide input for quality surveillance.

**Water plasma**

In order to reduce the post-processing of cut parts and also to obtain higher cutting speeds at reduced energy consumption, there is a move towards cutting with oxygen, O2, instead of nitrogen, N2 (Fig. 5).

Investigations appear to indicate that the running costs, in terms of the consumption of gas, energy and consumables, end up at the same cost level, whereas the use of O2 improves the dross-free range of plate thickness and permits a 40% increase in cutting speed in 12 mm steel plate. For example. As the energy that is needed is lower as a result of the exothermic reactions with O2 in steel, changing to O2 increases the possible plate thickness for a given size of power source.

When it comes to the precision and accuracy that can be obtained, it is likely that water-plasma cutting, no matter which gas is used, will lose its foothold to some degree and laser cutting will be preferred. In the case of new installations, it will be possible to take the special precautions that are needed to operate a laser-cutting installation, while paying due consideration to its environmental implications. This will be touched upon at a later stage.

**Laser and dry plasma**

The dry processes have the inherent advantage of being dry, which means that they do not need a water table, a considerably more expensive arrangement than a
comparable table arrangement for a dry process. What is more, handling cutting with water tables takes time and introduces other disadvantages like those touched upon earlier.

However, the dry processes also have inherent disadvantages when it comes to the environmental issues of noise and, particularly in the case of laser, radiation. As has already been said, the use of laser cutting will increase as a result of reduced dross appearance, greater accuracy and the higher productivity that can be obtained with dry cutting tables.

The author believes that this will take place, although the actual cutting speed for laser versus plasma-water at the present time, for 20 mm MS, for example, is 1 m/min compared with 3 m/min.

For shipyards in particular, when they invest in new cutting facilities, it will be attractive to change to laser and it will also then be possible to handle the environmental issues in the ideal manner. In short, this will result in the complete removal of the operator and other manual activities from the installation site and a change to complete reliance on remote control, remote handling and remote surveillance. For the supplier and designer of these cutting installations, there is still some way to go before all the facilities for the programming and surveillance of the relevant cutting parameters are available, but it is thought that this will be the trend in development as far as laser is concerned. While this is being implemented, we shall probably see the development of the laser technique towards coping with thicker material while maintaining the level of precision. The current standard is 25–30 mm for MS. The double-focus technique is one way of achieving this.

Finally, it is worth noting that laser cutting lends itself to interesting precision jobs such as contour cutting, with or without bevel, in one operation on two-dimensional or three-dimensional workpieces, also including the cutting of small holes, with or without chamfers. Figures 6 and 7 illustrate this development in laser cutting.

At present, fine-beam plasma cutting has potential for thin plate cutting which can be further exploited when the appropriate solutions for reducing or avoiding the inherent noise level are introduced.

Fine-beam plasma cutting is very attractive investment-wise, as compared with laser cutting, for a number of applications where the highest precision is not necessary (compare with Fig. 2). At the same time, it is to be expected that, within the foreseeable future, fine-beam plasma will increase in capability from the present maximum 20 mm thickness up to a maximum of 50 mm, both figures referring to MS.

**Summary**

Over the years, environmental issues have become an increasingly important point on the agenda when it comes to the design of cutting systems. The current technology, its productivity merits and deficiencies are briefly described, as they relate to present and upcoming environmental issues in the fields of dust, fume and gases, noise, radiation and ergonomics in general. With that as the starting point, a discussion of the outlook for improvements—the ways and means of establishing improved environmental conditions, while paying due consideration to productivity, as seen through the eyes of a manufacturer of cutting systems, featuring a horizon stretching into the next millennium—is presented.

**About the author:**

**Klaus Decker,** Dipl.-Ing. is Managing Director of ESAB CUTTING SYSTEMS.
New ESAB OK Tubrod 15.13 for robot welding at Fincantieri

Report by Ferruccio Mariani, ESAB Italy

Esab Italy contribute to the success of robot welding at the Monfalcone yard, as part of its extensive service to the yard.

The Monfalcone yard is the location for FASP, the European Union project for Fully Automatic Ship Production. The experience that is acquired here will enable European shipyards to build competitively in terms of cost and time in relation to yards in the Far East.

Overall view of massive robot welding installation

The state-owned Monfalcone yard specialises in large luxury cruise vessels. The fabrication procedures are conventional; plate cutting and bending, panel line, plate assembly to panels, followed by the build-up of sections and final hull construction.

When it comes to FASP, Fincantieri is in the process of refining each stage to achieve the highest possible level of automation.

Robot welding for ships

This represents a step-up from mechanisation methods which involve GMAW processes for downhand and vertical-up welds.

The traditional role of robots for welding industrial products, often aided by workpiece manipulation, has to be re-thought, because shipbuilding robots have to work over considerable distances across and along panel lines. While this is not easy, linear positioning on this scale is well within the capability of current technology.

The other essential factor for robot welding is consistency in the fit-up of plates, profiles and so forth on panels. In this context, the skills of the Monfalcone yard have been very useful.

The “robot-friendly” cored wire

As a major supplier of SAW consumables at Monfalcone, Esab was well placed to give advice. The yard naturally had an open choice of cored wires from suppliers worldwide. Optimum results required:

- Rutile type to conform with established shipbuilding welding practice
- Use of CO2 gas for economy
- Good feedability to minimise stoppages
- Positional capability to handle fillet welds in PB/2F and PF/3F positions with full penetration
- Wide parameter box to avoid critical setting of welding current, voltage and wire speed
- Highest possible productivity

To satisfy these requirements, it was agreed to base the new wire on the FILARC PZ6113 type of rutile flux-cored wire, as this would meet all the above requirements. This was proven with robots, and for shipbuilding, in both 1.2 and 1.6 mm sizes.

With application support from Esab cored wire development, Esab Italy presented the new OK Tubrod 15.13 to the yard for evaluation. This joint helped to reinforce the well-established position of Esab Italy as a welding supplier to the Monfalcone yard.

Tests and subsequent production proved that OK Tubrod 15.13 met all the requirements. It is truly robot-friendly!

The yard is currently obtaining experience from the supply of cored wires from a 200–235 kg Marathon Pac, thus avoiding downtime for changing spools. Wire feeding at distances of up to 20 m is compatible with the long columns on which shipbuilding robots are mounted.

The future success of FASP, and indeed all robot welding for shipyards, ultimately depends on the performance of cored wires when it comes to optimising productivity.

In this context, Esab’s marketing organisations, will definitely be adding many new advantages.

About the author

Ferruccio Mariani joined ESAB in 1991 as product manager for FCWs and SAW products. He had previously worked for 17 years at Ansaldo ABB in Milan in Italy, firstly as a welding supervisor at the Nuclear Welding Dept. and later as a welding engineer with responsibility for procedure qualifications and welder training activities. His current position at ESAB SALDATURA in Italy is consumables marketing manager.
ESAB has sold two sets of Friction Stir Welding (FSW) equipment to Sapa in Sweden. Sapa is a leading aluminium extruder and fabricator of aluminium products. With this investment, Sapa will also be able to include the production and welding of large profiles and panels in its business.

The first ESAB SuperStir™ system Sapa purchased from ESAB is equipped with double welding heads. The machine will be used to manufacture parts for the automobile industry. This is a breakthrough for FSW in the automotive industry. The second ESAB SuperStir™ machine will be used for the production of large panels and heavy profiles with a welding length of up to 14.5 metres. This machine has three welding heads, which means that it is possible to weld from two sides of the panel at the same time, or to use two welding heads, positioned on the same side of the panel, starting at the centre of the workpiece and welding in opposite directions from one another. Using this method, the productivity of the FSW installation is substantially increased.

Sapa is a member of the Gränges Group, which employs 4,500 people in 12 countries and is one of the world’s largest producers of extruded aluminium profiles. Sapa, Skandinaviska Aluminium Profiler AB, is the Swedish subsidiary company with 1,400 employees and a turnover of SEK 2.1 billion. In Sweden, Sapa has the leading position with a market share of more than 50%.

ESAB was the only welding equipment manufacturer to join The Welding Institute (TWI) as an original R&D contributor to develop the Friction Stir Welding process in 1992. ESAB decided to market the process under the name of ESAB SuperStir™ and supplied its first commercial FSW machine to Marine Aluminium of Norway in the autumn of 1996.

To date, upwards of 120,000 metres of weld have been performed without defects. Since then, ESAB has also delivered four FSW systems to The Boeing Company in the United States, which uses the equipment to produce components for the Delta family of rockets, used for launching communications satellites.

The Friction Stir Welding method
The friction generated by a rotating tool, in combination with high pressure, plasticises (softens) the surrounding material and the tool transports material using a closed keyhole technique. Welds can be made in any position using single-pass or double-sided techniques. The process requires no special surface preparation before welding, such as machining or etching. As no melting occurs, no filler material or shielding gas is used, the joints are free from distortion and porosity, have no lack of fusion and do not change their material composition. Another advantage of FSW is that it is now possible to weld aluminium alloys which could previously not be welded, with excellent results. Moreover, this is a very environmentally-sound method, as there is no spatter, no toxic fumes and no noise during welding.

The method is ideal for the production of ships, offshore platforms, railway carriages and bridges and for applications within the automotive and process industries.

Complete production programme
ESAB, the world’s leading company in welding and cutting, is now also the world leader when it comes to the production of equipment for Friction Stir Welding. ESAB can offer a number of different SuperStir™ systems for workpieces ranging from very small up to 10x30 metres for applications of all kinds.

Additional information is available from:
ESAB Welding Equipment AB
Attn: Lars-Göran Eriksson
Phone: +46 584 81160
Fax: +46 584 411721
Email: larsgoran.eriksson@esab.se
New multi-wire SAW equipment for the longitudinal welding of pipes

Esab Welding Equipment in Sweden is delivering pipe-welding equipment to a pipe mill in Indonesia. The pipe mill will produce longitudinal welded pipes within 24–42" (610-1,067 mm) in lengths of between 20-40′ (6-12.3 m).

After pressing the plate to produce a pipe, the pipe is fed through a fixture for continuous CO₂ tack welding externally. The pipe is then placed on a carriage, turned 180°, and internal welding takes place when the pipe enters a 13-metre long boom with a three-electrode, submerged arc welding head.

The control system for the welding is an integrated part of the centralised product tracking control system, in which each pipe is individually tracked throughout the manufacturing process.

In principle, the welding control panels at each welding station are based on a PLC, where the operator can supervise the process.

Welding parameters are programmed centrally and fed to each PLC via the computer network. The operator’s task will be to key in individual pipe numbers and supervise the process.

After welding is completed, all the parameters, together with any deviations and the individual pipe number, will be fed back to the central computer system.

When Esab designed this new pipe-welding equipment, the aim was to create a flexible modularised system, which could be incorporated in existing booms, carriers and pipe carriages at different customer facilities.

ESAB Group establishes worldwide headquarters in Atlanta

Ray Hoglund, chief executive of ESAB Group worldwide, announces the opening of the company’s headquarters in Duluth, Ga., a suburb of Atlanta.

“We chose the Atlanta area because of its quality of life, world-class airport, international recognition and reputation as one of the top 10 cities in which to establish a global headquarters,” said Hoglund.

Joining Hoglund at ESAB Group is Frank Engel, who will serve as the company’s chief financial officer. Engel was previously chief financial officer for ESAB Welding & Cutting Products. Hoglund has also promoted two other ESAB employees to positions at the company’s headquarters. Anders Backman has been appointed group vice-president for welding consumables and Mart Tiismann has been appointed group vice-president for welding equipment. Both previously worked for ESAB Europe.

ESAB Group manages the company’s operations in North America, South America, Europe and Asia. The company’s goal is to improve its global leadership position by developing an international approach, which is based on the strength of its national and regional teams.

The company’s new address is: ESAB Group, 2180 Satellite Boulevard, Suite 375, Duluth, GA, 30097. The phone number is (678) 475 5100 and the fax number is (678) 475 5101.
Esab acquires AlcoTec

Esab Welding & Cutting Products has acquired AlcoTec Wire Company, located in Traverse City, Michigan, USA. AlcoTec was purchased from Aluminium Company of America (ALCOA) and Aluminium Technology Corporation. It is the only fully-integrated aluminium wire producer in the USA.

“AlcoTec is the technological leader and the world’s largest producer of aluminium welding wire,” says Ray Hoglund, chief executive of Esab worldwide. “Not only is AlcoTec the foremost expert in the production of aluminium welding wire, it also consistently brings innovations to the applications engineering side of the business. The acquisition of the company will enable Esab to strengthen its commitment to the research and development of aluminium filler metals, building upon our history of product innovation.”

Aluminum fabrication is increasing in a variety of industries, including aerospace, automotive, bridges, military, railways, recreation, shipbuilding, trucking and utilities. Design engineers and fabricators like the unique characteristics of high strength and low weight aluminium has to offer.

AlcoTec currently employs 130 people. Brothers Bruce and Steve Anderson, who are partners in Aluminium Technology Corporation, will continue to manage the day-to-day operations at AlcoTec.

“This is an important acquisition for Esab,” said Nigel Smith, chief executive of Charter, the parent company of The Esab Group. “The complementary nature of AlcoTec’s leading position in aluminium wire will further strengthen Esab’s position as the global market leader in welding.”

FILARC PZ6105R
The robot-friendly cored wire

Robotic welding is characterised by high duty cycles, often with high welding currents, and by frequent stop starts. In addition, a high and especially consistent weld quality is required. This places demands on the welding consumable that can not fully be met by standard wire products like solid and cored wires developed for semi-automatic MIG welding.

FILARC PZ6105R is a metal-cored wire optimised for robotic welding by means of feedability, dependable starting and a well balanced welding performance. It is suited for single- and multi-layer fillet and butt welds in the PA and PB position.

Improved feedability
A optimised wire finish and optimal coiling ensures constant delivery in long liners, while avoiding feeding problems due to contamination of liners and contact tips. It is available in FILARC MarathPac bulk packaging to avoid downtime from coil changing.

Dependable starting and a stable arc
The special formulation provides a reliable calm arc ignition with minimal spatter, and reduced risk of wire burn-back. Improved current transfer assures a stable arc and a very low spatter level along the weld.

Productivity
PZ6105R comes in Ø 1.4 mm, the most versatile size for most robot welding equipment. Above a level of 250 A, it provides excellent weldability and optimal productivity, up to very high currents. A wide range of fillet sizes can be covered.

Smooth weld appearance
Flat fillet welds with good tie-in and penetration favour the appearance and fatigue performance of robot welded workpieces.

### Classification
- **AWS**: A5.18-93: E70C-6M H4–
- **EN**: 758: T 42 4 M 3 H5

**Shielding gas**
- Ar/15–25%CO₂
- EN 439: M21

**Weld metal composition [%]**
- C: 0.03–0.07
- Si: 0.60–0.90
- Mn: 1.40–1.80

**Deposition data in: Ar/CO₂**
- Diam: 1.4 mm
- Stickout: 20 mm

<table>
<thead>
<tr>
<th>I [A]</th>
<th>V_wire [m/min]</th>
<th>Dep. rate [kg/h]</th>
</tr>
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<tr>
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<tr>
<td>350</td>
<td>12.1</td>
<td>7.2</td>
</tr>
<tr>
<td>450</td>
<td>18.5</td>
<td>11.2</td>
</tr>
</tbody>
</table>

**All weld metal mechanical properties**
- **Rated strength, R_m [MPa]**: 510–600
- **Yield strength, R_y [MPa]**: ≥240
- **Elongation, A_5 [%]**: ≥22
- **Impact value, A_v (ISO-V) –40°C [J]**: ≥47

### Approvals (Pending)
- TÜV
- DB
- DNV
- ABS
- GL
- LR
- BV

**Positions**
- **⊥**
- **⊥**

**Current and polarity**
- **DC +

**EN 758 Hydrogen class**
- **H5**
The Oscar Kjellberg Award

Professors Göran Alpsten and Jan-Olof Sperle have been awarded the 1999 Oscar Kjellberg Gold Medal for their many years of work in the field of fatigue and the anti-fatigue design of steel structures. The medals were presented by Bertil Pekkari, President of the Swedish Welding Commission at its spring meeting.

Göran Alpsten, M. Eng, and Dr. Techn, was involved in the production of Construction Welding Standards and was chairman of a working group for the anti-fatigue design of welded joints. He has been active in a number of major projects that utilise advanced welded constructions, including Globen athletics arena in Stockholm and the Oresund Fixed Link between Sweden and Denmark.

Jan-Olof Sperle, M. Eng, has also been working on the problems of fatigue. In his doctoral thesis, entitled “High strength steel for lightweight structures”, fatigue-related issues play an important part. Dr. Sperle has been the Swedish representative on the IIW Fatigue Committee since 1975.

The Kjellberg Gold Medal is the Swedish Welding Commission’s most prestigious award. It was established in the memory of Oscar Kjellberg, inventor of the coated welding electrode and founder of ESAB. According to the rules, the Kjellberg Award may be given to individuals who have made major contributions to the benefit of welding and related disciplines. It was presented for the first time in 1941 and has been presented on four occasions, in 1944, 1992, 1994 and 1995.

Esab Norway helping to save history

One of Esab Norway’s largest and oldest customers has designed and manufactured a truly unique steel/glass structure which is going to protect the ruins of a cathedral from the 13th century in Hamar in Norway. The structure is a tubular framework comprising some 4,500 pieces of piping which have been welded together with complicated joints. In all, around 1,000 different geometries have been calculated for these pipe ends. In addition, some 3,000 attachment points for glass have been welded, about 1,700 of which were different.

Are we entitled to “manipulate” the workings of history and nature?

The structure has created some heated discussions and headlines in Norway. Should ruins really be enclosed? Are they not part of the landscape and, as such, should they not be allowed to stay as they are and perhaps crumble in peace? Opinions differed on these points, but the Norwegian Central Board of National Antiquities decided that the ruins should be enclosed. Because, since the mid-19th century, it has restored the ruin extensively, but it still feared that the brickwork would soon collapse as a result of erosion. This takes place primarily as a result of frost erosion and constant fluctuations around 0°C should therefore be avoided. Enclosing the ruin makes it possible to control the temperature and keep it above freezing point all year round.

Since the construction work was completed, the negative criticism has stopped, however. “Incredible but true. A real success! The first impression of the glass building was fantastic.” “Building something new is the only way to spotlight the historical. Inside, the ruin appears as something magnificent and unexpected.” “The contrast between the new and the old has enabled something of a ‘resurrection’ to take place.” These are just some of the many comments that have been heard since the work was completed.

Esab’s contribution will be part of the future

AB Esab in Larvik in Norway supplied all the consumables for the construction and the customer naturally also uses a fair number of ESAB machines in his production process. The construction in itself is unique, as all the steel structures fitted together perfectly during assembly, thereby demonstrating that all the previous production processes had been performed correctly. As a result, the customer is extremely satisfied with his own and his suppliers’ performance in this complex project. It is pleasing for Esab to be able to contribute to such a deserving cause, an attempt to preserve this unique building for posterity.
Laser welding
A mature process technology with various application fields

by Johnny K Larsson, MSc, Volvo Car Corporation, Sweden

The utilisation of laser welding in manufacturing industries has increased rapidly during the last few decades and can be regarded as a more or less mature technique. During welding, the very high power density in the focal point evaporates the material and causes a narrow, deep entry hole which moves through the workpiece as the beam is moved. This is known as "key-hole" deep penetration welding [Fig. 1]. During welding, an inert gas (normally helium or nitrogen) flows through a nozzle to the workpiece surface in order to prevent oxidation.

The most common laser for high power welding is the carbon dioxide laser (CO2 laser). This laser emits light with a wavelength of 10.6 µm. The laser gas mixture used in CO2 lasers consists mainly of helium, to ensure the removal of generated heat, carbon dioxide, the laser-active medium, and nitrogen, in which a gas discharge creates the energy necessary for excitation. The CO2 laser is especially cost-effective when used for the high-speed welding of comparatively thin-walled structures like car bodies. The disadvantage of this type of laser is that it requires a sophisticated system to distribute the laser beam to the workpiece. This also means that the work stations are not as flexible as they might be. The quality of the beam is also reduced if it is necessary to transfer the laser beam via many mirrors.

The other dominant laser source is the Nd:YAG laser. This type of laser has a wavelength that is ten times shorter (1064nm) than that of the CO2 laser. The laser-active medium, neodymium (Nd3+-ions), is located in a solid crystal made up of yttrium-aluminium-garnet and is usually rod-shaped. The optical excitation in pulsed lasers (p-lasers) generally occurs by means of krypton flash-lamps, whereas krypton arc lamps are used in continuous-wave high power lasers (cw-lasers). The principal advantage compared with CO2 lasers is that the light from the Nd:YAG can be transmitted to the workpiece by optical fibres and can therefore be more easily integrated into a large variety of systems.

However, the development of more flexible and efficient lasers is continuing and in recent years we have seen new products, such as diode-pumped Nd:YAG lasers or direct-acting diode lasers, starting to be used in commercial production.

This article will present a number of laser welding applications. Naturally, from the author’s point of view, several examples have been taken from the automotive industry, but, to highlight the various opportunities presented by laser processing, some examples will also deal with micro technology welding, as well as the welding of plastic components. At the end, some examples of new process development are also reviewed.
Automotive applications

Some of the keywords in automotive manufacturing today are quality, flexibility, high productivity and cost effectiveness. Laser welding appears to meet all these requirements and the proof can be found in the impressive number of lasers already in operation today at automotive companies.

Roof laser welding can be more or less regarded as state of the art among automotive manufacturers and some European car manufacturers will now be mentioned, simply to illustrate how well-established the laser welding process is.

Volvo

Volvo started roof laser welding in series production in connection with the introduction of the 850 model in early 1991. The reason for choosing laser welding for the roof of the 850 was the strength requirements for the upper roof rail, a crucial part of the Volvo system known as SIPS (Side Impact Protection System). As a result, the roof rail had to be designed as a closed section [Fig. 2].

This restricted the opportunity to join the roof to the rest of the body to either adhesive bonding or laser welding. Both concepts were evaluated in early proto-types and the test results indicated that the laser would be superior. When it came to both product requirement fulfillment and the reliability and environmental aspects in production terms, the laser welding technique emerged as the winner.

The installation at the Ghent plant consists of a 6 kW CO₂ laser, a five-axis gantry robot and a beam delivery system including five mirrors, the last of which is of the parabolic, focusing type.

Three different, easily exchangeable laser welding heads with adjacent focusing alternatives are included. The welding speed is around 5.5 m/min, a prerequisite in order to correspond to the station cycle time.

The fixation of the sheets in this overlap joint (0.8mm uncoated to 0.8mm 8µm electro-galvanized steel) was associated with major difficulties, as one of the sheets was part of a closed beam section with no access for a stationary backing fixture. The problem was finally solved with the aid of a Pressure Roller Device (PRD). This consists of a copper wheel mounted on the laser head and featuring adaptive z-compensation through the telescopic action of the laser head. The wheel squeezes the sheets together with a point force of about 250N and guarantees at the same time that the focal point is located in the optimum position vis-à-vis the workpiece. The welding is then carried out using helium, at 30 l/min, as the shielding gas.

As laser welding cells for car body manufacture represent a considerable investment cost, Volvo had to investigate cost reduction potential when the decision was made to start production of the 850 model at the Swedish Torslanda Plant as well in the summer of 1994. The main objective for the new laser welding station was to ensure cost optimization without undermining the experience acquired from the earlier Ghent installation. This has resulted in a far more simple and flexible robot system using two 125 kg standard robots and two Zeiss telescopic tubes for the beam guidance system, instead of the very dedicated gantry robot.
[Fig. 3]. The capital investment for this system is approximately 25% lower than that of a conventional gantry robot, but it has produced satisfactory results in terms of weld quality and uptime.

When the new Volvo S80 was introduced in the spring of 1998, the Torslanda cell had to be equipped with a second laser source of 6 kW in order to meet capacity requirements, as both this model and the S70 (formerly the 850) were manufactured in mixed production on the same assembly line. This means that both sides are now being welded simultaneously, whereas the previous process solution welded one side at a time. The length of the seam weld on each side of the car body is approximately 1.4 metres for saloon models and 2.3 metres for estates. The two welding cells in Ghent and Torslanda have so far produced more than 1,000,000 car bodies. This represents a record of 4,000,000 metres of continuous laser beam welded joints.

**BMW**

When it launched its latest 5 Series model, BMW presented laser welding as extensive as 11 metres on each car body and 12,000 metres of laser welding is performed every day at the Dingolfing Plant.

Two 5 kW CO2 lasers, each connected to an industrial robot, perform roof to uni-side welding utilizing Zeiss telescopic tubes and a roller device with a pressure force of 700N to minimize the gap between the parts that are being welded. The welding is done intermittently (10 weld stitches/side) at a speed of 5 m/min. This welding operation extends from the roof to the rear cross-member joint [Fig. 4]. For quality assurance purposes, the “Jurca” system has been introduced. This system monitors plasma radiation and plasma temperature.

At a sub-assembly station, two more 5 kW CO2 lasers weld the dashboard panel. In the first operation, the lower cowl is welded continuously to the firewall. A closure panel (upper cowl) is loaded on top to create the closed cowl section. This is welded continuously utilizing both lasers with adherent robots to make two weld lines in parallel to avoid distortion. This sub-assembly represents about 4.5 m of continuous welding and contributes greatly to the improved torsional stiffness of this car body model.

For the assembly of the trunk lid, BMW utilizes the so-called “beam-trap” technique. If the laser beam has an S-polarized shape, it is possible to focus it on the joint by reflection. This technique also offers the advantage that the parts to be welded are less sensitive to positioning accuracy. The outer trunk lid consists of two parts, an upper and a lower one, which are welded together using
this technique. The welding is performed by a 2 kW CO₂ laser operating in a gantry robot system. For the firewall and trunk lid applications, a seam tracking system must be utilized.

**Ford**

At Ford’s Cologne Plant, the roof of the Scorpio estate model is welded to the sides of the body using an Nd:YAG laser. The 2 kW laser produces the beam through a fibre-optic delivery system to the welding nozzle, which is fitted on an industrial robot. The welding nozzle has a guide roller fitted to it, which runs parallel to the welding optics. This guide roller squeezes the panels together in the region of the focal point of the laser beam with a programmed clamping force, while keeping the focal point position constant. By employing this laser technology, Ford claims that the roof channels can be made smaller in the roof seam area, which would not have been possible using resistance spot welding. In addition, the stiffness and seal tightness are enhanced through the continuous joint, while noise generation and sealant operations are reduced.

**Audi**

At present, both Audi and VW use Nd:YAG for roof laser welding. Audi does this on the A3 and A4 Series models manufactured in Ingolstadt, whereas the company is still using the CO₂ technique for the equivalent welding work on the A6 models produced in Neckarsulm. At the Audi Ingolstadt Plant, 1,800 cars are produced every day. A4 and A3 models are produced on three parallel body assembly lines.

The first line began operating in 1994. The A4 limousine model is assembled here, utilizing a 2 kW Nd:YAG laser for welding, with a second for back-up. The application is the vertical welding of the C-pillar (150 mm) and transversal welding in the “Q-glass” opening. Both applications are performed as overlap welds in electro-galvanized coated sheets with a welding speed of 2 m/min.

On line two, the A4 limousine and A4 Avant (estate model) are produced in mixed production. For the Avant model, the application is roof to uni-side welding; 60 weld stitches are made on each side, representing a total weld length of 1.6 metres. The reason for choosing stitch welding is to avoid distortion in the car body. A specific welding sequence is used for the same reason. As the amount of welding is higher in this cell compared with the previous one, two 2 kW Nd:YAG lasers operate in parallel to weld the roofs of the Avant models and the C-pillars and Q-glass openings of the limousines. A third laser is used as back-up in the event of equipment breakdown. In this cell, power monitoring is used as a quality control measurement; the effective power at the workpiece is not allowed to drop below 1450W. The cycle time on both lines is 83 seconds.

The third and most recent line was inaugurated in 1996 in conjunction with the launch of the new Audi A3 Coupé. Also in this cell, two 2 kW lasers work in parallel with a third laser as back-up. The application here is also roof welding, but with a slight difference compared with the A4 Avant. In the area between the A- and B-pillars, stitch welding is utilized with 19 stitches with a length of 15–20 mm on each side. For the rear part of the roof, continuous welding is performed. The total weld length is 1,075 mm on each side and the material thickness is 0.9 mm for the uni-side and 0.8 mm for the roof. Both components are electro zinc-coated. The welding speed is 1.6 m/min, which means that the cycle time is a little longer compared with the other two lines — 88 seconds. For quality assurance, the monitoring system developed by LaserZentrum Hannover is used. It supervises the power, weld length and the gap between sheets.

In all the cells, “CORGON18” is used as the shielding gas, 20 l/min. This is a gas mixture of 18% CO₂ and 82% Ar. As both parts to be welded are zinc-coated, it has been necessary to develop and use a cross-jet to protect the nozzle from any back spatter of evaporating zinc. Availability in the Audi Ingolstadt laser cells is said to be close to 99%.

**Volkswagen**

Volkswagen introduced Nd:YAG laser welding in connection with the launch of the new Passat model. Production at the Emden and Mosel plants utilizes 2 kW systems. As both the roof panel and the uni-side are made of zinc-coated steel, VW has chosen not to make a conventional overlap weld in order to avoid zinc spatter and unstable welding conditions. Instead, the weld is positioned at the edge of the roof panel, which means that, apart from avoiding the above-mentioned welding problems, the weld speed can be considerably increased. This means that the welding which is performed without using shielding gas (the same as in the case of the Ford Scorpio) can be done at a speed of 5–6 m/min, whereas the corresponding figure for normal overlap welding would be approximately 3 m/min. To be able to perform this edge welding, a seam-tracking system (Scout-sensor) had to be introduced. The contributions from laser welding are said to be improvements in strength, quality and precision. Moreover, the increased styling and design freedom is also mentioned.

One of the main reasons why VW chose to invest in the Nd:YAG technology was a desire also to be able to weld inside the car body. This is now being utilized as some variants of the Passat models are equipped with a rear seat back panel to improve the torsional stiffness of the car. Due to the flexibility offered by the robot-mounted welding nozzle with integrated fibre optics, it is possible to intermittently perform this fairly complex welding procedure and still maintain acceptable weld quality.

**Renault**

At the Sandouville plant, Renault has now started to investigate the three-dimensional laser welding of complete car bodies. This in-
Accurate positioning using expensive external fixation devices

<table>
<thead>
<tr>
<th>Step</th>
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<th>Accuracy after each step</th>
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</thead>
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<tr>
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<tr>
<td>2. Laser welding</td>
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<td>±1µm</td>
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<tr>
<td>3. Removal of the tools</td>
<td>0.5 s</td>
<td>±3µm (final)</td>
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<tr>
<td>Total</td>
<td>10.6 s</td>
<td>±3µm (final)</td>
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Laser adjustment method

<table>
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<th>Step</th>
<th>Time per step</th>
<th>Accuracy after each step</th>
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</thead>
<tbody>
<tr>
<td>1. Rough positioning using simple tools</td>
<td>1 s</td>
<td>±3µm</td>
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<tr>
<td>2. Laser welding</td>
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<td>±5µm</td>
</tr>
<tr>
<td>3. Removal of the tools</td>
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<td>±6µm</td>
</tr>
<tr>
<td>4. Laser manipulation (closed loop with computer vision)</td>
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<td>±0.3µm (final)</td>
</tr>
<tr>
<td>Total</td>
<td>2.1–2.6 s</td>
<td>±0.3µm (final)</td>
</tr>
</tbody>
</table>

Table 1. The influence of laser adjustment on accuracy and processing time.

volves the four- and five-door versions of the Laguna model. The application is stitch welding in the windscreen opening. Nine 60 mm long welds connect the roof and the windscreen cross-member. Furthermore, three welds on each side, ranging between 50–100 mm in length, attach the uni-side to the inner part of the A-post. Welding is facilitated as all the parts are uncoated apart from the body uni-side. The intermittent method of welding in the A-pillar area is used to avoid welding three sheet layers. Two Nd:YAG lasers offering 3 kW at the workpiece are used, together with 600 µm fibres for beam delivery. The welding nozzles are attached to two robots and equipped with a roller fixture, which, with the support of a pneumatic cylinder, produces a point pressure of 250N in order to minimize the gap between the sheets. The focal length is 200 mm and “CARBON45”, the standard shielding gas for arc welding procedures at the plant, is used for laser welding as well. The cycle time is 45 seconds, which requires a welding speed of 4–5 m/min. By introducing a cross-jet function, the service life of the protective glass for the focusing lens has been increased from 100 to 1,000 hours.

Micro technology

Laser micro-processing has grown to become a mature technology for many parts in the electronics industry. It has not only replaced conventional technologies but, as a result of the redesign of product parts dedicated to the new technology, it has also enabled improved product quality and new products. The low cost of ownership, the reliability of the equipment, the high yield of the process, combined with the high accuracy and flexibility, have made the laser a very valuable tool.

Laser spot welding is an accepted technology in the electronics industry. Every manufacturer of TV and computer monitor tubes uses this technology for the assembly of the electron gun. Typically, 150 tiny laser welds, applying pulsed Nd:YAG lasers and fibre beam delivery systems, are used to sub-assemble the cathodes, the electron optic grids and lenses and, finally, to assemble the gun. It would be true to say that the quality of modern TV picture tubes could not be realized without laser spot welding.

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Together with a continuing trend towards miniaturisation, new products that require micron and sub-micron accuracy in mass production are being designed. Because laser welding involves the introduction of heat into the product, if only to a very limited extent, thermo-mechanical deformation and displacement have to be considered at the design phase, so that they can be utilized in laser adjustment operations. Several thermo-mechanical mechanisms are known to produce both bending and shortening in a part. In this way, it would be possible to manipulate several degrees of freedom in a product that is mounted on the structure. Using this new technology of laser ma-
nipulation for the adjustment of parts, elaborate positioning procedures using expensive, complicated tools can be replaced by simple tools and the final accuracy will be produced by laser adjustment [Table 1].

It is clear that laser processing in the electronics industry has become a mature technology and a large number of parts can only be manufactured using this technology [Fig. 5]. Using solid state lasers with high beam quality, it is possible to create weld sizes in the 100 µm range. By adapting the beam geometry and pulse shape for each individual welding application, it is possible to minimize the distortion as well as the contamination of the welded part.

**Welding plastics**

The application of lasers has created new opportunities in the welding of thermoplastic components, which until now has primarily been performed using ultrasonic or vibration welding. For this area of application, Nd:YAG and diode lasers, offering radiation near a wavelength of 1 µm, are suitable for use because of the absorption characteristics of plastic materials. These absorption characteristics in the materials to be welded are very important when using laser. The absorption and thereby the penetration depth of the radiation is a function of the laser beam and material composition. Photothermal materials absorb the CO₂ radiation in the surface layer and cause the vaporisation of the material. The Nd:YAG and diode radiation penetrates into the polymer sample and produces a melting volume which is necessary for the welding process. The absorption properties can be influenced by the content of pigment in the plastic material. So black parts can be welded together, because being black to the eye differs from being black or absorptive for the laser.

Virtually all thermoplastic materials can be laser welded. The joining of two different materials is possible if the material combination is weldable, i.e. the temperature ranges in which the materials are liquid must overlap. Fluorinated and temperature-resistant materials can be welded with lasers, as well as PMMA and ABS, or plastic to metal. In a combination of increasing interest to the automotive industry, TPEs can easily be joined with thermoplastics using laser radiation [Fig. 6].

A keyless entry product has a black keypad overlap-welded onto the black case [Fig. 7]. The keypad is coloured with a pigment transparent to laser radiation, while carbon is used as the absorptive pigment for the case. Welding these keyless entry cases is the first example in which the laser is being used in an industrial application. Laser welding was chosen because the keypad is the final part of the assembly and is welded after all the electronic circuits are mounted. Other welding processes would have led to increased scrap rates. Ten diode lasers with an output power of 30 W each are used to perform the welding process and the welding speed is in the range of 5 m/min.

Using the laser also permits excellent quality control of the weld seam during production. Modern electronics and sensor technology provide the means for on-line monitoring and process control of process parameters.
the melt zone temperature during the welding process. The exact temperature needed for the material can be maintained by controlling the laser power with the temperature signal obtained from the measurement. The temperature control unit can be integrated into the optical head and guarantees reproducible and constant quality in the weld seam, independent of material inhomogeneity resulting from previous processing steps.

**Future developments**

**High Power Diode Lasers (HPDL)**

High power diode lasers usually have wavelengths of between 790 and 980 nm. Compared with CO2 and solid state lasers, HPDLs cannot be focused down to a comparable spot size, due to the higher beam divergence and lack of coherence between the individual diode emitters. The divergence parallel to the diode arrays (called the slow axis) is about 10° (full angle), whereas the divergence perpendicular or vertical to the diode arrays (called the fast axis) is up to 50° (full angle). Due to this divergence astigmatism, special optics are used to compensate and, owing to the poor beam quality, short focal length focusing optics are used to obtain a reasonable focused spot.

A single diode bar currently produces about 30 W, although with future developments it is hoped to raise the power to 50 W. A typical bar is 0.1 × 0.6 × 1.0 mm in size [Fig. 8]. Output powers in the kilowatt range can be produced by stacking bars together to form an array or stack. A stack with an output power of 1 kW is approximately the same size as a shoe box [Fig. 9]. The beam from a 1.4 kW HPDL can butt weld 0.8 mm mild steel using a 50 mm focal length optic and a processing speed of 1 m/min. The HPDL can also weld zinc-coated materials.

Due to the low power density which is produced, only heat conduction welding has so far been possible. Initial tests in Germany show that a 1.4 kW HPDL can butt weld 0.8 mm mild steel using a 50 mm focal length optic and a processing speed of 1 m/min. The HPDL can also weld zinc-coated materials. Another area of interest is the conduction fillet welding of 1 mm thick stainless steel which produces a cosmetically excellent weld. The laser welding of aluminium is also expected to undergo improvements. With the HPDLs with an 800 nm wavelength, aluminium shows good absorption. All over the world, large-scale efforts are now being made to improve the beam quality of diode lasers in order to extend the use of this type of laser to other “difficult-to-weld” applications.

**Plasma Arc Augmented Laser Welding**

One interesting approach is to combine a Nd:YAG laser of fairly low power with a plasma welding torch equipment, the so-called PALW technique (PALW = Plasma Arc Augmented Laser Welding) [Fig. 10].

This will increase the level of efficiency, making the price of a system of this kind favourable. The plasma is directed into the laser keyhole using the laser plasma. A cross-section through a weld of this kind shows the deep penetration effect of the laser, combined with the wide weld bead of the plasma. Geometry of this kind is favourable from the automotive crashworthiness and durability point of view. As a larger volume of melted material is produced, the positioning between the sheets to be welded can be less precise.

**Double focus welding**

The hybrid techniques, like the above-mentioned PALW or lasers...
combined with MIG or TIG torches, generally result in fairly bulky arrangements, which limit the accessibility of the welding head. To obtain similar results, i.e. extremely deep penetration and a broader weld seam, different optical arrangements can be used to split and focus the laser beam on two (or even more) spots. This double focus or twin spot technique is now being evaluated at many laser laboratories worldwide and it has so far produced some promising results in connection with welding aluminium, for example.

Remote Laser Welding

Utilizing what is designated as “Remote Laser Welding (RLW)” [Fig. 11], deep penetration welding can be accomplished over large areas and from a distance greater than 1 metre, using a slab discharge CO₂ laser. The beam is steered over ±20° by galvo mirrors and the focal length can be changed over 600 mm. This system can produce five spot welds a second. Furthermore, each of these spot welds can be performed in a complex pattern, which increases the volume of the molten material, by oscillating or wobbling the beam. This enhances the strength and accommodates gaps.

The rapid welding, in combination with the fact that the remote welding system is less expensive than a laser robot, results in a dramatic reduction in the cost of each spot weld.

Summary

The large number of laser welding applications described in this article clearly indicates that the laser is regarded as an accepted and mature processing tool for assembly operations. The advantages of laser welding include the high processing speed, resulting in a narrow heat affected zone and almost no distortion in the finished part. This contactless method is also easy to robotize, which is a necessity if it is intended for use in high volume production, in the automotive and electronics industries, for example. Moreover, the high quality weld can be controlled on-line using various integrated monitoring systems, developed especially for laser welding.

With the on-going process development described at the end of the article, the possible applications for laser welding in the manufacturing industries will be more or less unlimited. In fact, for some applications, no alternative joining method can be found.

I therefore foresee a rapid increase in industrial laser welding and I can promise that what is described here should actually be regarded as the “tip of the iceberg” of what is to come.

Figure 11: Principle of the remote welding technique.

About the author

Johnny K Larsson graduated from the Lund Institute of Technology in Sweden in 1975. After spending eight years as an engineer in the heavy truck industry, he joined Volvo Cars in 1986. Since then, he has been responsible for the R&D programme at the Body Engineering Department, covering areas such as materials technology, joining methods, structural analysis and simulations.

In recent years, he has focused his technical skills on joining technologies for current and future car body concepts and is therefore acting as project manager for a number of activities in this field within the company. He is also involved in different EU CAR and international projects dealing with joining techniques.

Through the years, Mr Larsson has become a well-known person on the international scene and has served as session chairman at numerous automotive and laser conferences such as FISITA, ISATA, NOLAMP and so on. He also contributes to the continuing education of European automotive engineers through his involvement in organizations like EUROMOTOR and ELA (European Laser Academy).

Mr Larsson holds a number of trust positions in the Swedish Welding Commission and in the Swedish Association for Laser Applications in the Manufacturing Industry, among others.

Over the years, Mr Larsson has presented a number of technical papers focusing on the innovative research work performed within the Volvo Group.
Energy costs have often been disregarded as a minor part of the total welding cost. This article demonstrates that poor power source efficiency consumes unnecessary amounts of extra energy, leading to costs which can be avoided by choosing the right equipment.

When it comes to the welding process, there are major differences in the energy consumption of the welding methods. In addition to the energy costs, the heat input is a welding parameter of great significance for the metallurgical effects and thermal distortion.

We also have to consider the environmental effects of the unnecessary electricity consumption, the heat generation and the waste of our common resources. Other aspects related to the use of electric energy are also discussed, including the problems associated with electromagnetic compatibility (EMC) and the possible harmful effects of electromagnetic fields for human beings.

**Power sources**

Typical efficiency values for arc welding power sources are 75–85%. This means that, for a load of 500 A/40 V, the losses can be in the range of 3–6 kW. The value depends on the type of power source that is used. Inverters are smaller and they also have less power loss than traditional machines, see Fig. 1.

Normal welding is not continuous and the arc time factor has to be taken into account when calculating the energy costs. During the time when it is switched on but not in use, the equipment has open circuit losses. The old rotating welding converter could have open circuit losses of more than 1 kW, large MMA welding machines 300–400 W, while the modern inverter power sources perhaps have no more than 50 W.

If the power source is designed correctly, all the losses are dissipated without too great an increase in temperature in the sensitive parts, i.e. insulation material or semiconductors. If the internal cooling surfaces are clogged up with dust and dirt, the temperature increases and shortens the service life of the equipment. It is also important from a safety point of view to avoid overheating. A breakdown in the insulation between the primary and secondary windings in the transformer may enable the mains voltage to reach the welding circuit. If the secondary circuit is not connected to earth, this would be hazardous to the welder.

When choosing a power source for industrial welding, high efficiency is obviously an important economic factor. Even if the energy cost is just part of the total welding cost, it can be high enough to justify the extra investment cost required for energy-saving equipment. The losses from several machines in a workshop also contribute by helping to increase the temperature in an environment that is perhaps already too hot.

The dimensioning of the electrical installation depends on the total need for power but also on the power factor. The power factor is important when it comes to calculating the apparent power and the size of the fuses. Inverter power sources that have many good properties do not necessarily have a high power factor. If they are equipped with a Power Factor Correction (PFC) circuit, the power factor is increased and the necessary fuse size can be reduced.

If the welding transformer has a poor power factor, this indicates a phase shift that can be improved by phase compensating capacitors. The power factor of inverters mainly depends on a distortion in the shape of the current, a deviation from the sine wave.
wave. In this case, the above-mentioned PFC circuit is a possible way of helping to improve the power factor.

If the necessary welding energy is used at short intervals, as it is in resistance welding, for example, the mains must be able to deliver high electric power. This is comparable with the effect of a low power factor — the size of the fuses and the total cost of the electrical installation increases and can be high in comparison with the real need for electric energy as measured in kWh.

**Electrical and magnetic noise**

Semiconductors in welding rectifiers and inverters cause disturbances of higher frequency in both the mains and welding circuits. The highest frequencies make electrical noise that can interfere with radio communications, computers or other electrical equipment. The lower frequency ripple in the welding circuit must be filtered in such a way that it does not affect the welding properties. The current ripple of inverter power sources is of such an amplitude and frequency (20–100 kHz) that a risk of interaction with the welder must be taken into consideration. The experts are discussing whether there is a risk of certain types of cancer. The magnetic field can also produce heating effects. Using a simple test developed by the author, it was possible to measure the rate of increase in temperature by one degree Celsius a minute on a metal plate (simulating an implant) close to a welding cable. The high welding current which is common in resistance welding can interfere with the function of pacemakers.

**Choice of welding method**

One interesting point is to study the welding methods with regard to their need for energy. In addition to the cost of energy, the heat input is an important welding parameter. Too much heat input into the joint will reduce the impact strength and introduce thermal stress and distortion in the workpiece. More recent welding methods can achieve high welding speeds and low heat input. The diagram in Fig. 2 shows a comparison between different welding methods. The total energy for a one-metre long weld is calculated. It is interesting to see that, in spite of the low efficiency of lasers, laser welding can compete effectively with traditional methods like MMA. As a rule of thumb, the welding methods with the highest energy density usually have the lowest heat input.

![Fig. 1. Energy consumption per year for different types of MMA-welding power source. The differences depend on different efficiency and open circuit losses.](image1)

![Fig. 2. Total energy per metre needed for some different welding methods (4 mm steel plate). Power losses from the equipment are included in the calculation.](image2)

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**About the authors**

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**Joakim Hedegård** (b. 1961), Licentiate of Technology, has been working for nearly ten years in the area of welding, mainly with education and applied research projects. He is a former product manager at ESAB and Assistant Technical Secretary to the Swedish Welding Commission and will soon be joining the Swedish Institute for Metals Research as programme manager for the Joining Technology Centre.
Effect of interpass temperature on properties of high-strength weld metals

by Mike Lord, Gill Jennings and Every, Great Britain

Abstract
High-strength weld metals frequently have a microstructure consisting of martensite or a mixture of martensite and acicular ferrite. The alloying of the weld metal has to be designed so that sufficient hardenability to generate the required microstructure during cooling is obtained. It has been observed that the yield strength of such alloys can exhibit considerable variation in the range of 700-950 MPa for the same consumable electrode. The work presented here reveals one reason for these variations — that the cooling curve of the weld is close to the limit of hardenability of the material. This means that the microstructure obtained becomes sensitive to variations in the interpass temperature in multirun welds.

Introduction
Making a high-strength steel using a variety of well-established strengthening mechanisms is a straightforward procedure. Achieving toughness, which is the ability of the metal to absorb energy during fracture, is far more difficult. The essence of most alloy design is to obtain a reasonable compromise between strength and toughness.

Unlike wrought steels, welds cannot usually be processed to enhance the microstructure and properties once the joint is completed. Many welds that are used for structural steels cannot even be heat treated after deposition. As a result, there are limitations to the maximum strength that can usefully be exploited. A high-strength weld is therefore currently limited to a yield stress of about 900 MPa for most practical circumstances.

Untempered microstructures capable of resisting deformation at such large stresses are based on martensite or on mixtures of martensite/bainite/acicular ferrite. The alloys must therefore contain a sufficient content of austenite-stabilising elements consistent with the hardenability required to avoid other phase transformations. At the same time, the carbon concentration must be minimised to avoid excessive hardness when the weld is deposited. So, elements such as manganese, nickel, chromium and molybdenum are added as they improve hardenability and yet do not excessively strengthen the steel. A typical weld metal composition for manual metal arc welding is therefore:
Fe-0.05C-0.5Si-1Mn-3Ni-0.5 Cr-0.5Mo wt% with a strength of about 900 MPa and a Charpy notch toughness at –60°C of about 60 J.

It has been found that the mechanical properties of this and similar higher strength welds are variable, even though the chemical composition of the deposit does not change (1). In particular, the yield strength can vary (150 MPa), whereas the ultimate tensile strength does not vary as much. This is unsatisfactory from the customer’s point of view and indeed for the electrode manufacturer who has to supply electrodes to specification.

The purpose of the present work was to investigate the variability in the mechanical properties of these high-strength weld deposits.

Experimental details
Weld specifications
An experimental weld (multirun MMA) was fabricated according to ISO 2560 using a 20 mm thick plate filled with 30 runs (three beads per layer). An interpass temperature of 250°C was used.
Dilatometry
A Thermecmastor Z thermo-mechanical simulator was used to study the phase transformations occurring within the weld metal as a function of the applied cooling rates. The transformations were monitored using laser dilatometry. Specimens for use in the simulator were machined into cylinders with a length of 12 mm and a diameter of 8 mm. A hole with a diameter of 5 mm was drilled along the central length of the specimens, the reduction in material volume producing more accurate data. Heating the specimens was effected via an induction coil and cooling was similarly controlled using a combination of induction coil heating and jets of helium quenching gas.

In the production of a continuous cooling transformation (CCT) curve, the specimens were austenitised at 1,200°C for 10 minutes in order to reduce the effect of the austenite microstructure before each specific cooling cycle was applied.

Results
Mechanical testing
The results of the tensile and impact toughness tests are presented in Table 2.

Microstructure
Light microscopy has a resolution of about 0.5 µm at most. Observations revealed apparently plate-like features, but they were believed to represent clusters of plates which are much finer. The fine structure could not really be revealed and was not found to change much with its position within the multirun weld (Figure 1).

Thin foil observations using transmission electron microscopy revealed a fine microstructure comprising bainite plates with a width of the order of 0.3 µm. A typical TEM micrograph is shown in Figure 2. Electron diffraction proved the presence of retained austenite films between the bainitic ferrite plates. The crystallographic orientation between the austenite and adjacent ferrite was found to be consistent with that expected from a rational Kurdjumov-Sachs (KS) relationship (Figure 3).

The alloy contains a fairly low carbon concentration, so the ready observation of reasonably thick retained austenite films might be considered surprising at first sight. However, carbon is partitioned from the bainite after it stops growing and this stabilises the austenite which is enriched in carbon (2). In fact, the observation of these thick films can be safely taken to indicate the presence of bainite, which in low-alloy steels can be difficult to distinguish from martensite. Carbide precipitation was never found in spite of extensive investigations.

Dilatometry to produce a CCT curve
Further experiments using dilatometry were conducted to verify that the fine plates with intervening austenite represented bainite rather than martensite. If the observed transformation temperature remains constant for different cooling rates, it can be concluded that the final microstructure must be martensitic, since the martensite-start (Ms) temperature does not depend on the cooling rate for low-alloy steels (3). On the other hand, the temperature at which a detectable fraction of bainite forms does depend on the cooling rate, because the overall kinetics of the reaction can be described in terms of a C curve on a continuous cooling transformation (CCT) diagram.

A CCT curve was produced by cooling specimens at various rates ranging from 100°C/s to 0.05°C/s. Figure 4 shows the experimental CCT curve, along with the calculated Ms temperature (4) and a calculated MMA weld bead cooling rate with an interpass temperature of 250°C (5) denoted ‘250°C ITP’.

Table 2. Results of mechanical testing.

<table>
<thead>
<tr>
<th>Rp0.2 (MPa)</th>
<th>Rm (MPa)</th>
<th>A5 (%)</th>
<th>Z (%)</th>
<th>+20°C</th>
<th>0°C</th>
<th>-20°C</th>
<th>-40°C</th>
<th>-60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>872</td>
<td>922</td>
<td>22</td>
<td>67</td>
<td>102</td>
<td>95</td>
<td>87</td>
<td>79</td>
<td>64</td>
</tr>
</tbody>
</table>
The calculated weld bead cooling rate clearly cuts the CCT curve beyond the limit of hardenability in a region which should produce a bainitic microstructure. TEM micrographs showed fine plates which confirm a displacive mechanism of transformation. These two curves intersect at a position at which the gradient of the CCT curve is very large. Consequently, small variations in the cooling rate of the material could drastically alter the transformation temperature and thereby the resultant mechanical properties. This hypothesis led to questions concerning the possible causes of such variations. The problem was approached using a sophisticated method of pattern recognition, known more generally as neural network analysis.

**Neural network: the method**

There are difficult problems (such as welding) in which the general concepts might be understood but which are not as yet amenable to rigorous mathematical treatment. Most people are familiar with regression analysis where data are best-fitted to a specified relationship which is usually linear. The result is an equation in which each of the inputs \( x_j \) is multiplied by a weight \( w_j \). The sum of all such products and a constant \( C \) then gives an estimate of the output \( y = w_1 \cdot x_1 + w_2 \cdot x_2 + \ldots + C \).

It is well understood that there are dangers in using such relationships beyond the range of fitted data.

A more general method of regression is neural network analysis (6–9). As before, the input data \( x_j \) are multiplied by weights, but the sum of all these products forms the argument of a hyperbolic tangent. The output \( y \) is therefore a non-linear function of \( x_j \); the function which is usually chosen is the hyperbolic tangent because of its flexibility. The exact shape of the hyperbolic tangent can be varied by altering the weights (Figure 5a). Further degrees of non-linearity can be introduced by combining several of these hyperbolic tangents (Figure 5b), so that the neural network method is able to capture almost arbitrarily non-linear relationships. For example, it is well known that the effect of chromium on the microstructure of steels is quite different at large concentrations than in dilute alloys. Standard regression analysis cannot cope with such changes in the form of relationships.

One potential difficulty when it comes to the use of powerful regression methods is the possibility of overfitting data (Figure 6). For example, it is possible to produce a neural network model for a completely random set of data. To avoid this difficulty, the experimental data can be divided into two sets, a training dataset and a test dataset. The model is produced using only the training data. The test data are then used to check that the model behaves when presented with previously unseen data.

Neural network models in many ways mimic human experience and are capable of learning or being trained to recognise the correct science rather than nonsensical trends. Unlike human experience, these models can be transferred readily between generations and steadily developed to make design tools of lasting value. These models also impose a discipline on the digital storage of valuable experimental data, which may otherwise be lost with the passage of time.

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*Figure 4 Experimental CCT curve.*

*Figure 5 a) Three different hyperbolic tangent functions; the “strength” of each depends on the weights. (b) A combination of two hyperbolic tangents to produce a more complex model. Details about the methodology can be found in David Mackay’s article in *Mathematical Modelling of Weld Phenomena III.*

*Figure 6 A complicated model may overfit the data. In this case, a linear relationship is all that is justified by the noise in the data.*
Neural network structure

While there are many varieties of neural network, the type used in this work can be expressed diagrammatically as shown below. In this case, the network is composed of three “layers”. The first layer contains the model input data provided by the user, such as compositional details (simply as normalised values), the second “hidden” layer is an internal stage and describes the degree of complexity of the substructure of the network. The third “output” layer contains the predicted value of the parameter in question when running a calculation. Figure 7 shows a simplified network with five example input parameters.

The circles within the diagram are called nodes or units, so here there are five “input nodes”. The hidden layer comprises three hidden nodes and the output layer is simply a single output node. The number of nodes in the hidden layer limits the complexity of the possible relationships between the input and output nodes. The lines connecting the nodes represent mathematical functions performed on the values as they pass from the input to the output layer. In this network, hyperbolic tangent functions are utilised, as they are always single valued, exhibit both near-linear and non-linear regions and are relatively easy to manipulate. When performing a “prediction” using a neural network, data are operated on by a hyperbolic tangent function as they are passed between the input and hidden layers. This function is of the form:

\[ h_j = \tanh \left( \sum w_{ij} x_j + \theta_i \right) \]

where \( x_j \) are the normalised values of the input variables, \( w_{ij} \) are a set of “weights” associated with each input and hidden unit and \( \theta_i \) are bias values analogous to constants found in linear regression.

The values \( h_j \) are transferred from the hidden layer to the output layer via a second function of the form:

\[ y = \sum w_{ij} h_j + \theta_2 \]

where \( y \) is the value of the output node (e.g. yield strength), \( w_{ij} \) are a second set of weights and \( \theta_2 \) is a further constant known as a ‘bias’.

The numerous weighting coefficients and constants \( (w_{ij}, \theta_i, w_{ij} \text{ and } \theta_2) \) are required in order to provide the flexibility to calculate accurate output values from input data. At the heart of the neural network technique there are algorithms designed to evaluate these coefficients and constants in order to produce satisfactory results.

Training the network

Training involves repeatedly exposing the training algorithms to data for the network inputs (e.g. compositions) and, crucially, the output (e.g. yield stress). The data must come from a database relevant to the particular application in question. The quality of this database determines, at least in part, the final accuracy of the network predictions. The required size of the database may vary depending on the complexity of the problem that is being modelled. In general, the larger the amount of accurate data, the better the predictions of the resulting network. The training algorithms refine the coefficients and variables in the above equations by comparing the predicted and actual output values of the output node. Through a complicated back-propagation process, the computer program attempts to reduce the differences between predicted and actual values until they reach acceptably low levels. There is an additional problem with “over-training”, which means that the network can learn the examples in the dataset too well and will then be unable to predict values for different unseen compositions. This is analogous with fitting a complicated curve to a set of points that lie on a straight line, where the experimental errors have been modelled into the network rather than just the trend. Using a number of different hidden nodes and training on a randomly-selected half of the available data, the best network can be picked to strike a balance between modelling real trends and overtraining on noise in the data. The second half of the dataset is used to compare the predictions of this trained network (Figure 8). Ideally, plots of predicted versus measured values for both the training and testing halves of the dataset should contain equal degrees of scatter.

Figure 7 Graphical representation of a neural network. Some examples of input node parameters are also presented.
Two types of network were trained on data from 770 welds drawn from a variety of sources, the first giving yield stress as an output, the second ultimate tensile strength (10). Nineteen input variables were provided for each of these welds, fifteen of which were due to alloying elements, while the remaining four were due to the heat input, interpass temperature and tempering time and temperature values if applicable.

A number of different networks were trained and tested. In the case of the yield stress models, the five best models were then combined to create a “committee”. A committee of networks is superior to a single one as, collectively, they should capture the trends in the data more effectively. Each network within the committee was retrained on the complete dataset to provide greater accuracy before committee predictions were made. Similarly, a committee of four models was used in the predictions of ultimate tensile strength.

Investigation of tensile strength effects
As stated earlier, previous analyses of the weld microstructure had provided little insight into the cause of the observed variations in strength. However, dilatometer data in the form of a CCT curve had shown that typical MMA measured cooling rates could fall in a critical region. The hardenability of the weld metal caused plotted weld cooling rates to fall close to the “nose” of the bainite curve in a region of particularly high gradient. A calculation of this kind indicated that small variations in the weld cooling rate could considerably affect the transformation temperature. It was thought likely that such a variation in the displacive transformation temperatures of the material would have a large enough effect significantly to alter mechanical properties.

Compositional variations alone could not be held responsible for the large variations in yield strength reported for this material. It would seem more plausible to consider process parameters as being responsible. This rationale eventually led to the identification of the interpass temperature as a possible candidate for causing the strength variations. Large joints comprise many passes in order to deposit the required amount of material. Welds under construction cool at a rate determined by their environment, such as the degree to which the surrounding material acts as a heat sink and the temperature of those surroundings. If the interpass temperature is high, a subsequently deposited bead will cool at a reduced rate which, it was surmised, may be significantly lower, depending upon the temperature. The trained neural network as a research tool was now useful as it provided a means of...
temperatures of above 200°C. These are only realised at interpass temperatures when the weld metal is being overloaded. This ratio is desirable to have the yield stress to UTS ratio closer to 0.8 in predicting the effect of the interpass temperature on strength, both in terms of the absolute values and in the relative variation in the yield and ultimate tensile strengths. It is particularly encouraging that the model predicted that the difference between these two measurements of strength is a function of the interpass temperature.

**Conclusions**

There are three major conclusions that can be drawn from this work. By comparing transmission electron microscopy and diffraction data with measurements of transformation temperatures using dilatometry, it has been possible to prove that the high-strength weld cannot be fully martensitic at the cooling rates typical of welding. The microstructure will instead consist of a mixture of martensite and bainite, the latter consisting of bainitic ferrite separated by carbon-enriched films of retained austenite. These methods are recommended in circumstances where it is otherwise difficult to distinguish bainite and martensite (i.e. when the microstructure is very fine and the carbon concentration so small that carbide precipitation is prevented).

The second conclusion is that difficulties are to be expected with respect to the mechanical properties when the bainite and martensite transformations occur at temperatures which are not much above the nominal interpass temperature. This is because the cooling rate of the weld between the bainite and martensite start temperatures becomes very sensitive to the interpass temperature. Failure accurately to control the interpass temperature leads to large variations in the microstructure and hence in the mechanical properties.

Finally, a neural network model has been shown to be reliable in predicting the effect of the interpass temperature on strength, by using a network with a single hidden layer trained to become a British and European Patent Attorney.

**References**


**About the author**

Mike Lord graduated from Cambridge University with a degree in Natural Science, specialising in Materials Science 1995. He then joined the Phase transformation research group in Cambridge to do a PhD. His subject was phase transformations and properties of high strength weld metals. His work was sponsored by Esab and EPSRC. Mr Lord was awarded the Granjon prize 1998, Category 2 by IWW for his paper “Interpass temperature and the welding of strong steels”. Mr Lord is presently working at Gill Jennings and Every, training to become a British and European Patent Attorney.
“The technology of tomorrow” has already been implemented at BORSIG in Germany

by Dr. Ing Andreas Risch, Head of the Welding Engineering Dept. at BORSIG GmbH, Germany, and Mr Bengt Ekelöf, Senior Project Manager at Esab Welding Equipment AB, Sweden

BORSIG (a company within Babcock-Borsig AG), a famous supplier of pressure vessels and heat exchangers for the chemical and petro-chemical industries, has optimized its welding and cutting production process by implementing fully-automated systems for submerged arc welding (SAW) and oxy-fuel cutting.

An advanced, fully-adaptive SAW process is used at BORSIG for butt welds of up to 120 mm in joint depth. The multi-layer tandem SAW process is controlled by intelligent software which makes its own decisions for the complete welding operation.

The holes for nozzle intersections in the shell of the pressure vessel are cut by an industrial robot. Off-line programming for cutting holes with constant weld bevel angles or constant joint volume is performed using different macros.

The advanced welding and cutting systems are mounted on a multi-functional gantry which travels on rails. The gantry works in conjunction with two anti-creep roller bed stations, see Figure 1. This type of installation was specially designed by ESAB for the requirements of the BORSIG product range.

Fig 1. – The multi-functional gantry in operation at BORSIG.

Fig 2. Typical configuration of a combined reformed and synthesis gas heat recovery system.
**BORSIG products**

As one of the leading suppliers of complete Process Gas Waste Heat recovery systems and quench cooling systems for the chemical and petrochemical industries, BORSIG designs and fabricates different types of heat exchanger and pressure vessel.

The Quench Coolers are used for the rapid quenching of the gas effluent from cracking furnaces in ethylene plants. The main applications for the Process Gas Waste Heat Recovery Systems are ammonia, methanol, hydrogen and coal gasification plants.

Examples of components in these systems, manufactured by BORSIG, include:

- Process Gas Waste Heat Boilers
- HP Steam Superheaters
- HT Shift Waste Heater Boilers
- Boiler Feed Water Preheaters
- Gas/Gas Heat Exchangers
- Synloop Waste Heat Boilers
- Steam Drums

Fig 2 shows a typical configuration for a combined reformed and synthesis Gas Heat Recovery System.

Almost every pressure vessel or heat exchanger is a unique application, specially designed according to the requirements of the specific process or client specifications.

All these applications involve high gas inlet temperatures (up to 1,200°C), often accompanied by high process gas pressure up to 300 bar, as well as the generation of high-pressure steam (up to 140 bar).

**Quality requirements**

The design and manufacture of high-pressure equipment is strictly regulated in worldwide pressure-vessel codes like AD, ASME, BS, Raccolta, Codap, Stoomwezen, IBR, JS, AS and so on. The production quality, and the quality of the welding connections in particular, is very important because of the critical operating conditions of the pressure vessels. Imperfections in the welded zone are restricted to an absolute minimum (mostly min. Group B according to ISO 5817 or better).

Every pressure vessel containing longitudinal or circumferential joints in the shells or the inlet and outlet sections is subjected to complete non-destructive testing such as magnetic particle or dye penetrant checks, as well as 100% radiographic (RT) and/or ultrasonic (UT) examination. Nozzle welds are normally completely examined by UT.

Prior to weld production, a process qualification test (PQR), including intensive non-destructive and mechanical testing, has to be performed in order to verify that the properties of all welds match the requirements specified in the applicable codes and the base materials. The process which is going to be used in production is restricted to the qualified range of the PQR when it comes to base material group, thickness range, post-weld heat treatment (PWHT), range of welding parameters (e.g. pre-heating temperature, welding speed, voltage, amperage, interpass temperature and so on).

**Materials and welding technologies**

Due to the service conditions of the equipment that is going to be manufactured, many different steels are used to manufacture the pressure vessels and heat exchangers. The following materials are examples for the main parts (hull) of the above-mentioned pressure vessels:

- High strength C steels (e.g. SA 516 Gr.70) for shells of Steam Drums and WHBs
- C-0.5% Mo steels (e.g. 15Mo3) for shells and nozzles of Steam Drums and Quench Coolers
- High strength, temperature-resistant steels (e.g. 15 NiCu-MoNb 5 or SA 302 Gr.B/Gr.C) for shells and nozzles of Steam Drums, Process Gas WHBs or Synloop WHBs (steam side)
- C-1.25% Cr-0.5% Mo steels (e.g. 13 CrMo 4-5) for shells of WHBs (steam side) and for gas-inlet and gas-outlet sections, tube sheets or forged rings for process gas WHBs (gas side)
- C-2.25%Cr-1%Mo steels (e.g. 10 CrMo 9-10) and C-3%Cr-1%Mo steels (10 CrMo 9-10)
mod.) for gas inlet sections, shell, tube sheets and nozzles of synloop WHBs (gas side)

The above-mentioned or comparable steels were welded to themselves (e.g. shell-shell) or were combined with one another (e.g. shell-tube sheet). The thickness of the shells for steam drums and WHBs (steam side) generally ranges between 40 and 120 mm, the gas-inlet sections of synloop WHBs increase up to 250 mm. The diameter of the vessels can differ from approx. 1,000 mm (e.g. quench coolers) to 3,000 mm (e.g. WHB). Typical applications are shown in Figs 3 and 4.

Due to the wall thickness and in order to meet the required mechano-technological properties, most of the applications, especially the higher alloyed steels, require pre-heating during welding and cutting, as well as controlled energy input and restricted interpass temperatures during welding operation.

In order to prevent cold cracking, the high strength steels need to be pre-heated to between 150 and 250°C. Preheating within 200–250°C and 250–300°C is also required for C-1.25%-Cr-1%Mo- and C-2.25%Cr-1%Mo steels.

For circumferential joints, a U preparation with a weld bevel angle of 8° is normally used. Cones are welded to cylindrical parts using a V-joint preparation (complete opening angle 50°). Nozzle welds (set-in nozzle) were performed with a half-V preparation (weld bevel angle 30–40°). The main welding technologies are GTAW and SAW for the root pass and SAW for the fillet/cap layers and back welding.

In order to optimize the production quality and the efficiency of the welding operation, BORSIG has incorporated a large number of automated welding and cutting processes in its production process.

Examples include fully-automated, tube-to-tube sheet welding for heat exchangers with computerised orbital GTAW welding machines (multi-layer TIG technology with filler wire), automated GTAW hot-wire overlay welding for critical dissimilar joints, GMAW robot welding of double pipe Quench-Cooler elements, robot welding of special stiffener systems to thin tube sheet and CNC plasma or oxy-fuel cutting of plates using CAD data and macro-programming systems.

**BORSIG’s criteria for the choice of the advanced welding and cutting systems**

Up to the end of 1997, the submerged arc welding of circumferential and longitudinal joints, as well as the cutting of nozzle holes in shells and gas inlet/gas outlet sections, was performed exclusively with operator-controlled welding and cutting equipment. The quality of these operations was therefore mainly influenced by the knowledge and experience of the operators.

The use of CNC-controlled machines which require absolute programming is not suitable because the actual geometry does not always correspond to the nominal geometry (base material thickness, joint condition, accuracy of shells, misalignments and so on). Additionally, pre-programming the bead placements for the multi-run sequence leads to a reduction in efficiency due to the increase in downtime.

So, more effective automation required the implementation of intelligent and adaptive software that makes its own decisions for the entire operation. This was verified in 1997 by installing the welding gantry, including the advanced ESAB ABW technology for the SAW process and the robot cutting system which can be programmed off-line on a macro base. Only the chosen type of software guarantees the flexibility which is necessary in pressure vessel manufacturing which specializes in client-oriented solutions.

**The system**

The fully-automatic, multi-purpose gantry was developed by ESAB and the project was realised in close co-operation with BORSIG engineers. All the elements and programming units were designed with user orientation as the starting point.

The gantry has a fully-automatic, laser-supported submerged-arc ESAB ABW welding system (see Fig 5), which works in conjunction with two 150-tonne roller bed systems equipped with anti-creep units. This permits the welding of longitudinal seams up to 4,200 mm in length and circumferential seams with a diameter of up to 3,500 mm.

The special narrow roller bed design permits the rotation of vessels with attached nozzles or flanges with a maximum projection of 750 mm and a minimum
distance of 500 mm between two nozzles or attached parts respectively.

At wall thicknesses of up to 120 mm, which covers 95% of all BORSIG applications, fully-automatic adaptive tandem welding can be performed. At thicknesses of up to 135 mm, mechanized tandem welding with the ESAB ABW head is possible. In the event of thicker wall thicknesses of up to 250 mm, a second conventional single-wire welding head can be used.

In any case, all the automatic or semi-automatic operations were controlled by the main control PC, Fig. 6. Two 250-litre pressure tanks located at the base of the gantry automatically supply the integrated continuous flux recovery system with new flux.

Alternatively, different fluxes depending on the procedure can be supplied from the pressure tanks at the base. The flux system is equipped with built-in electrical heaters. Minimum flux consumption is guaranteed by integral flux suction and circulation.

An industrial robot of the ABB IRB 2400/S4 type, equipped with a flame cutting (oxy-fuel) burner system, is mounted on a carriage which is installed perpendicular to another carriage at the main horizontal boom of the gantry, Fig. 7. Both carriages are installed as linear external robot axes which are used to position the robot and, if required, as additional robot axes during cutting operations. The cutting of nozzle holes, programmed on an off-line, macro-supported basis, is possible at wall thicknesses of up to 150 mm.

The system permits the cutting of holes with a diameter of up to 1,500 mm. The maximum ratio between the hole cut-out and the diameter of the course is 0.68. This results in a minimum shell diameter of 2,500 mm if a hole of 1,500 mm is to be cut.

Additionally, the gantry can be used as a multi-functional platform for fitting and welding nozzles and the other attachments to the vessels. For this purpose, the platform can be flexibly modified using removable insulated floor plates. The whole gantry and the roller bed systems can be positioned free on rails over a length of 45 m. All the main energy and data transfer cables were installed under the floor in cable chains covered by movable floor plates.

**The ESAB ABW adaptive joint fill program**

The ESAB ABW adaptive tandem welding system mounted on the gantry can handle both circumferential and longitudinal welding in a fully-automatic joint filling procedure. This is possible thanks to the intelligent software in the system.

True measurement data from the joint profile measured by an optical sensor during welding determine both the required level of the welding parameters on a con-
ABW weld fill procedure.

different tasks in the adaptive area and geometry along the joint line, Fig 8.

The number of beads in fill and cap layers

The unique ESAB ABW weld technology is designed to give manufacturers dealing with high quality butt welding a 100% automatic multi-layer technology, thereby enabling them to produce a defect-free weld fill, even if the joint geometry deviates from the nominal configuration.

The configuration of the ESAB ABW system was specially modified according to BORSIG requirements for flexible production. The modified system can also verify joints between shells and thicker flanges (step on one side near the weld), as well as joints between shells and cones, with the automatic generation of a smooth transitional contour between the two parts.

Registration and documentation of the welding operation

Continuous, fully-automatic, multi-run tandem welding for many hours with limited operator surveillance requires not only excellent man-machine communication (MMC), Fig 10, during the weld fill operation, but also a report system which explains how the work has been accomplished.

The ESAB ABW operating system software installed at BORSIG includes a report system in which welding and positioning data from the operation are registered in two separate files – the Weld Report file and the Log file.

In the weld report, all the installation parameters such as wire type and wire dimension, flux type and permissible interpass temperatures are stored, together with the specified process parameters such as welding voltage, welding current and welding speeds and their report, alarm and stop limits. All the important events during welding, such as start, stop(s), re-starts, exceeded report limits and warnings for flux level, high or low interpass temperature, are stored in the weld report. All the events are stored together with the actual date, time, weld layer, weld bead and position in the joint. Should the event be an exceeded process parameter, the parameters at the time in question are also stored.

In the log file, the position and process parameters are continuously registered (every 20 mm). A normal log file report for a thick-walled welding object could fill 1,000 pages.

Robotic oxy-fuel cutting of nozzle holes

Due to the saddle contour of a tubular intersection in a cylindrical shell, the programming of the hole-cutting operation is mathematically complicated.

In order to simplify the program procedure, a computer-based, off-line programming system of the ARAC type is used.

Two macros verify the calculation of the saddle contour and transfer it to robot co-ordinates. Cuts with either a constant groove opening or a constant weld volume can be made. The operator only puts the following data into the macro:

Shell diameter
Wall thickness
Diameter of the hole/shell intersection
Angle of the weld bevel
Cutting parameters (e.g. pre-heating time, gas parameters, cutting speed and so on)
Off-set for position of the cut-out and the cut width.

After transferring the program from the off-line PC to the robot control unit and putting the robot in the cutting position, a measuring program is started prior to the operation.

A special measuring sensor mounted at the burner tip performs a stepwise control of the surface at the location of the cut-out in a test mode.

Deviations from an optimum cylindrical surface are corrected in the macro by setting an addi-
vessel design.

more flexibility in the pressure absolute minimum. This permits calibrating to nozzle positions to an

system reduces the restrictions regulation with the anti-creep sensor

sign of the roller beds in combination with the anti-creep sensor

of ±1 mm. The special narrow design

of the rollers and, after some rotation

tions which are required for syn-

chronization, its horizontal posi-

tion remains stable within a range

of ±1 mm. The special narrow de-

sign of the roller beds in combination with the anti-creep sensor system reduces the restrictions relating to nozzle positions to an absolute minimum. This permits more flexibility in the pressure vessel design.

After a minimum of time for calibration and parameter setting, the welding process can be started directly. During welding, the operator only supervises slag removal and visually checks the weld quality from the bottom (floor). Downtime is reduced to an absolute minimum – interruptions are normally only required if the filler wire (100 kg wire coils) has to be renewed. One of the most important points is the improvement in quality, which is no longer influenced by the operator’s practical experience and knowledge.

Due to the adaptive weld fill functions in the ESAB ABW system, the repair rate has been reduced dramatically in comparison with conventional semi-automatic SAW machines. After sufficient operator training, only defect-free joints have been produced.

Using the robot system to cut nozzle holes has significantly reduced the number of working steps that were previously necessary. It is no longer necessary to mark the cut-out contour on the shell surface. The downtime caused by handling and positioning conventional mechanized cutting machines is avoided completely. Moreover, the effective cutting time has been reduced by half because the cut-outs are performed in one step instead of the normal two (straight cut and angle cut as separate operations).

Cutting is performed with high accuracy when it comes to wall thicknesses of between 50 and 150 mm. The maximum diameter deviations for the cut-out are ±2 mm and the weld bevel angle differs by no more than ±1°. This high accuracy influences the fit-up of the nozzles and the following welding operation performed using SAW nozzle welding machines very positively.

Another very important point is the human factor. Operators and welders are no longer exposed to high temperature radiation due to the required high preheating temperatures, because all the fully-automatic operations can be supervised from the floor. Moreover, if nozzle fit-up and nozzle welding or other operations are performed from the movable and flexible platform, the insulated floor plates protect the fitters and welders.

The quality results produced by the fully-automatic welding and cutting operation are not dependent on the operator’s practical knowledge or his/her concentration. On the other hand, it has been found to be advantageous if experienced SAW operators and cutters handle the system, because of their “feeling” for the processes. Due to the user-oriented design of the process control units, only basic PC knowledge or basic experience of CNC cutting applications are required.

Conclusion

Installing the new technologies for adaptive welding and automatic robotic oxy-fuel cutting at BORSIG’s heavy-duty plant has clearly increased productivity. The high level of automation ensures a high degree of flexibility with a simultaneous high level of quality. Downtime is significantly reduced compared with similar plants and this reduces the number of hours spent on machining.

Effect of the gantry installation in production

Immediately after installation, it was clear that the multi-purpose gantry improved productivity, as well as the quality level, very effectively. After one year of successful operation with the system, it can be established that many synergies are helping to increase the efficiency of heavy vessel production.

The anti-creep function of the specially-designed roller bed systems produces important advantages during welding start-up and actual welding.

Since all the industrially manufactured shells, rolled from plates, show deviations from an ideal cylindrical contour, it is impossible to avoid creep in the vessels or vessel parts without this function. In the past, the adjustment of the conventional roller beds in order to minimize creep required a great deal of time (sometimes more than one shift).

With the new system, the vessel only needs to be positioned on the rollers and, after some rotations which are required for synchronization, its horizontal position remains stable within a range of ±1 mm. The special narrow design of the roller beds in combination with the anti-creep sensor system reduces the restrictions relating to nozzle positions to an absolute minimum. This permits more flexibility in the pressure vessel design.
The objective of increasing machine availability is part of the specification for any new machine under development. However, this objective can only be realised if a range of important factors are taken into consideration.

If the causes of machine downtime are analysed, it will soon be established that, apart from the machine itself, the machine operator, the lack of properly trained service personnel and an inadequate supply of replacement parts all affect downtime.

An increase in availability can only be achieved by implementing a series of actions which take account of the overall situation.

The foundations for high availability are, of course, laid at the machine design stage.

Solutions that had been well-proven over a number of years were employed in the development of a range of medium machines for the autogenous and plasma processes, as well as for a new range of laser machines. These solutions included the track guidance system in the longitudinal direction and the latest engineering developments.

When selecting components for both the new ranges, the emphasis was placed on high reliability.

Universal, overall design concepts have a decisive effect on machine availability. From the mechanical design and the electrical system to the user interface, the ranges exhibit the same concepts and functions.

The kit system is designed in such a way that individual modules are used for various machine sizes, thereby minimising the variation in parts for the complete range. The larger series this produces does not simply result in more cost-effective production, shorter delivery times and an improved supply of replacement parts. It also produces a general improvement in quality with a lower failure rate. Reliable mechanical construction and electrical components alone are not sufficient.

Controller technology, user interface, machine operation and maintenance also have a decisive effect on machine availability. Incorrect operation, perhaps with serious consequences, and downtime can only be avoided if the operator is in full control of his machine.

Universal controller concepts and operating structures for all
cutting technologies, together with standardised and modular machine-interface programming, facilitate worldwide service and training for our machines. The continuation of this concept, and in particular the integration of technology-aided measures, such as the automatic setting of process parameters using databases or the integration of difficult process cycles with the controller, enhance the user-friendliness of our machines, which is in turn reflected in reduced downtime.

The use of these methods enables us noticeably to improve the already high availability of our machines.

This task will also be the subject of ongoing development and will be included in the specification for each machine.

The market call for increasingly narrow tolerances for cut parts, pledges of guaranteed quality and the employment of high quality cutting technology with lasers and water jets make it necessary to address the quality requirements for machine tools.

Due to the high geometrical flexibility, laser-beam and water-jet cutting are the preferred methods for the manufacture of workpieces with complicated shapes in intermediate quantities down to the production of single parts. The increasing demand in this market segment can be largely traced to these considerations and has led to a three- or five-axis module being needed for these tools as a basic machine, depending on requirements. ESAB-HANCOCK has also responded to this challenge and has brought a five-axis portal machine onto the market, with a high-performance CO₂ laser system.

Machine networking and integration into the material flow at a production facility in economically viable configurations represent a market challenge for machines and system suppliers.

ESAB-HANCOCK has demonstrated that these solutions are possible. In 1996, five-axis plasma and autogenous profile production centres were incorporated into the production facility at a Korean shipyard.

“Ready for the new world of automation”

It is wise not to lose sight of this objective. The automation of production cells and their integration into the production organisation leads to more and more complex networked systems.

In automation engineering, separate worlds are coming together to form integral systems. Specialised technologies, such as PLCs and CNCs, mix with classical data processing. Information technology offers numerous ways forward. New and combined systems offer improved rationalisation potential, but they require thorough personnel training. Relying on “learning by doing” results in acceptance problems and start-up difficulties. The advantages of these systems may include:

- Self-monitoring of the machine
- Display of servicing points
- Automatic process monitoring
- Detection of process errors, introduction of correction routines and so on

Fig. 2. Universal controller family with the same user guidance system.

Fig. 3. Setting process parameters on the NCE controller family.
Human interaction during production is reduced to a minimum

Information technology will not simply influence complex systems in the development of cutting machines. “Stand-alone” systems down to the small-machine level will also be affected by information technology, offering the user scope for rationalisation. Developments here are oriented towards process data optimisation, process monitoring and the early detection of tool wear. This makes the best use of machine performance and guarantees uniform production quality.

ESAB-HANCOCK has also set a benchmark here and pioneered developments in this direction. Autogenous process monitoring systems for small and medium machines are our contribution. The advantages of these machines for the user are obvious.

The machines can be operated in part without supervision and without the risk of producing scrap when a process error occurs.

More and more companies are demanding productivity increases and higher technical availability in their machines. A significant market requirement in this connection is preventive maintenance.

Here, too, information technology is offering us new ways to prepare cutting machines to meet the market challenge. ESAB-HANCOCK is already offering diagnostic systems which supply data for process monitoring, as well as providing a foundation for further developments in preventive maintenance.

Modern CNC controllers from ESAB-HANCOCK contain the latest in information technology with DNC (Direct Numerical Control) interfaces ensuring the reliable data transfer of cutting programs from Windows host computers to the CNC.

Modern communication techniques enable the visualisation and logging of current machine status and processing states via feedback on DDE (Dynamic Data Exchange) servers to WINDOWS (in real time, the Micro-
soft communications standard for process and production automation enables easy operation and integration with existing communication networks).

Some examples showing the scope for rationalisation for the operator of these systems are given below.

The DDE report client monitors the DDE server and writes the accumulated times, distances and, where applicable, fault numbers in an ACCESS database. This means not only that a standardised output from the report generator is possible, but also that users who have MS-ACCESS available can use the data for other purposes and for their own applications.

Concluding remarks
The market is demanding increasingly precise components with high quality cutting results, along with higher machine availability. These features constitute the motivation for innovation among machine manufacturers and are helping to move thermal cutting closer to the central point of production.

With modern cutting systems, it is possible to incorporate operations which are normally carried out by drilling and milling into the cutting systems. The marking and surface cleaning processes are also being integrated in cutting systems. Depending on the profile of machining require-
Fig. 10. The most varied connection methods to controllers are possible. No matter serial, telephone or Ethernet connections are used, the data is transferred reliably.

Fig. 11. The remote monitoring of machines enables an overview to be obtained of the machine status and quick interventions to be made when failures occur.

ments, it is possible to unify machine investment and to cut workpiece idle times dramatically so that the cutting centre becomes a profitable production tool.

About the author
Rainer Schäfer graduated from university in 1984 with a master’s degree in mechanical engineering. After having worked in areas including research and product development at Atlantik and Heyligenstadt, he joined ESAB-Hancock in 1995. He now has the title of Technical Director and is responsible for R&FD mechanics and electronics.

Fig. 12. The “Report Generator” produces status reports with the following information from the data gathered in a database:
- Date and time
- Program number
- The following from three processes:
  - Number of tool activations
  - Processing times
  - Path distances travelled
- Fast travel (distance and time)
- Overall program running time
- Fault log
Fabricators pleased with increased submerged arc productivity from cored wires

Improved welding technique has now matured

By Martin Gehring, ESAB GmbH, Solingen, and Shaun Studholme, ESAB UK Ltd.

In Svetsaren 1-2/96, we dedicated an article to submerged arc welding with special cored wires developed by ESAB, in which we discussed industrial applications from Finland where the method was pioneered. In the meantime, the technique has matured and has been adopted by fabricators across Europe. They benefit from productivity advantages resulting from higher deposition rates, as well as the avoidance of plate edge bevelling, a smaller weld volume and a reduced number of layers. Before discussing industrial applications from Germany, the Netherlands and the United Kingdom, the authors re-introduce the theme.

<table>
<thead>
<tr>
<th>Metal-cored</th>
<th>AWS</th>
<th>CMn</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK Tubrod 14.00S/OK Flux 10.71</td>
<td></td>
<td>F7A2-EC1</td>
</tr>
<tr>
<td>Basic flux-cored</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OK Tubrod 15.00S/OK Flux 10.71</td>
<td>CMn</td>
<td>F7A4-EC1</td>
</tr>
<tr>
<td>OK Tubrod 15.24S/OK Flux 10.62</td>
<td>1Ni</td>
<td>F8A6-EG-G</td>
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<tr>
<td>OK Tubrod 15.25S/OK Flux 10.62</td>
<td>2.5Ni</td>
<td>F7A8-ECNi2-Ni2</td>
</tr>
</tbody>
</table>

Table 1: ESAB OK Tubrod cored wires for the submerged arc welding of normal-temperature and low-temperature steels.
**Introduction**

Submerged arc welding (SAW) is widely recognised as a very productive welding process, offering the following advantages:
- A high deposition rate due to the use of high welding currents
- A high travel speed
- A reduced incidence of cold laps and slag inclusions
- A smooth weld surface with good tie-in
- No spatter, no fumes

The productivity of SAW is further optimised with variants such as twin arc, tandem and metal-powder addition, but these methods normally require large-scale investments in equipment.

The productivity of single-wire SAW can, however, be increased significantly by substituting specially-developed cored wires for solid wires. In the majority of applications, this requires no additional financial expenditure as the existing equipment is adequate.

**Product range**

The range of ESAB OK Tubrod cored wires for submerged arc welding is reviewed in Table 1.

- Both OK Tubrod 14.00S and 15.00S are Grade 3 approved, in combination with OK Flux 10.71, by the major ship classification societies, as well as TÜV and DB.
- OK Tubrod 15.24S and 15.25S are designed for low-temperature applications in offshore fabrication, for example. They are used in combination with OK Flux 10.62.

Both OK Flux 10.71 and 10.62 are basic agglomerated fluxes.
Advantages of cored wire

The deposition rate of cored wires exceeds that of solid wires of the same diameter by up to 20% when welded with the same current (Figure 1).

The resistance heating is higher with cored wires, because the current-conducting cross-section is concentrated in the sheath. The higher current density results in a higher melt-off rate and thereby a higher deposition rate. This effect is even more pronounced with SAW than with gas-shielded flux-cored arc welding, because much higher welding currents are used.

In all the applications discussed below, fabricators benefit directly from improved welding economy due to an increased deposition rate converted to higher travel speed.

Additional advantages, such as a reduction in weld volume, fewer beads, the avoidance of plate edge bevelling, plus a wide range of welding currents which can be used with the same diameter, are more dependent on the specific application.

Industrial applications

Meyer Werft, Papenburg & SSW Fähr- und Spezialschiffbau GmbH, Bremerhaven, Germany

Both yards, Meyer Papenburg and SSW (the former Seebeck Werft), changed from solid wires to cored wires as the consumable for the double-sided submerged arc welding of butt joints in plate fields. Both use the same cored wire/flux combination OK Tubrod 15.00S (4.0 mm)/OK Flux 10.71. In both cases, the single-head welding of 17 mm thick plate is performed.

In comparison with the previous application with solid wire, the travel speed for a single-layer, double-sided weld went up to 60 cm/min (see Figure 2).

In addition, it was no longer necessary to bevel the plate edges before welding, because of the secure penetration of the cored wire. Normally, the yards would give the joint a Y-preparation. The avoidance of bevelling was crucial to both yards, as it accounts for major cost savings.

KRAFFT-Walzen, Düren, Germany

KRAFFT fabricates rollers and cylinders for paper and textile plants. One of the welding jobs consists of attaching tube halves to the inside of rollers (see Figure 3). The rollers are 2.9 m wide with a diameter of 1.5 m and have a wall thickness of 5 mm. This was previously done using SAW with solid wire.

After changing to OK Tubrod 14.00S, the travel speed for welding these fillet welds was increased by more than 100%, as a result of the higher deposition rate and the use of a smaller throat size, which was made possible by more secure penetration.
The total welding costs were reduced by 45%.

Hydrowa, Eindhoven, the Netherlands

Hydrowa B.V. specialises in the design and fabrication of hydraulic cylinders with a length of up to 22 m for a variety of industries including offshore, dredging, automotive and food (Fig. 4).

Recently, the company equipped its workshop with a new ESAB submergible arc welding station consisting of a movable MKR 300 column and boom, a stationary ESAB A2 Minimaster SAW automatic welder, an LAE 1000 power source and two ESAB 10RTN manipulators.

With the new station, Hydrowa adopted submerge arc welding with cored wires to weld the circumferential joints of hydraulic cylinders (Fig. 5). The automatic SAW equipment and the power source are selected to handle cylinders with a diameter of 15 to 400 cm. The SAW machine has a maximum current of 800 A, feeding solid as well as cored wires with a diameter of up to 4 mm.

The cored wire/flux combination OK Tubrod 15.00S/OK Flux 10.71, produces productivity advantages over submerge arc welding with solid wires.

First of all, OK Tubrod 15.00S with a diameter of 3.0 mm can be applied directly over a TIG-welded root run without burning through, because a welding current as low as 200 A can be chosen, producing reduced penetration and an excellent tie-in. For the same application, SAW with solid wire requires a second layer with GMAW before SAW can be used, because a 3 mm size solid wire requires a welding current of at least 300 A.

In addition, filling runs can be performed with a welding current of up to 600 A with the same wire size. In this case, Hydrowa benefits fully from the increased deposition rate from cored wire which is converted to a travel speed of 60–80 cm/min. As a 3 mm solid wire would produce 40–60 cm/min., there is a substantial improvement in productivity.

Kværner Oil & Gas Limited, Scotland

Welding economy and integrity for offshore fabrication was tested using a welding procedure qualification for OK Tubrod 15.24S/OK Flux 10.62 in comparison with an established procedure for solid wire SAW. The welding procedure involved a 1/2 V-joint in 40 mm thick, grade 50D plate.

Tests were done at the same parameters as the existing procedure, but also at increased welding current and travel speed, according to table 2.

Tested at the same parameters, thicker beads are deposited because of the increased deposition rate. The mechanical properties show that this does not lead to loss of low-temperature toughness, whereas an arc time reduction of 21% is obtained.

At a higher welding current, while selecting a travel speed giving the required bead thickness, arc time is reduced by 27%.

Additional tests prove that mechanical properties remain satisfactory after stress relieving. Moreover, the combination OK Flux 10.62/OK Tubrod 15.24S is CTOD-tested, making it a very interesting option for more productive submerge arc welding in offshore fabrication.

<table>
<thead>
<tr>
<th>Procedure test results</th>
<th>Solid wire</th>
<th>OK Tubrod 15.24S</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of runs</td>
<td>25</td>
<td>20  (–21%)</td>
</tr>
<tr>
<td>Arc time (min.)</td>
<td>35</td>
<td>29  (–27%)</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>581</td>
<td>510</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>646</td>
<td>588</td>
</tr>
<tr>
<td>CVN (J) –40</td>
<td>69</td>
<td>159</td>
</tr>
<tr>
<td>–50</td>
<td>43</td>
<td>147</td>
</tr>
</tbody>
</table>

Table 2. OK Tubrod 15.24S/OK Flux 10.62. Welding procedure qualification for offshore fabrication compared with SAW solid wire.
An important question for the welding and cutting industry relates to likely developments beyond the year 2000. Some major trends and conclusions are already clear.

- More cost-effective production is still the single most important issue.
- Other strong driving forces are quality assurance and global environmental protection.
- System approach. Cost versus the performance and reliability of the entire production chain. A low cost for individual parts does not automatically lead to the lowest cost for the system. Instead, it might lead to sub-optimisation.
- A system is no stronger than its weakest link. This emphasises the importance of individual parts of the system. They could be gases. They could be filler metals. They could be power sources and so on. Improvements to individual parts must lead to the enhancement of the performance and reliability of the system. If the performance of individual parts is too good, however, this could lead to unnecessary costs. “Fitness for purpose” is therefore a key expression.
- Stronger focus on the end-user will increase the call for user-friendly systems, as well as the requirements relating to personal health and safety.
- Increased use of new or improved materials. This also includes surface-treated materials. Improvements could include lower weight, improved mechanical properties or corrosion-resistance properties. This will lead to suppliers of equipment and different consumables more frequently offering individual customer solutions. So, how will gases and gas application know-how help to meet customer demands in the future?

**System approach**

There are many considerations a company must take into account when it comes to sharpening its competitive edge. The functions and design of the product, its quality, appearance, as well as its impact on the environment, have to be weighed up against the cost. As if that were not enough, the working environment, health and safety and job satisfaction must also be included in the points for consideration. The final product and its features are in focus, rather than the result of individual steps in the manufacturing process. This is a system or module approach. The result of one operation may strongly influence the cost of performing a subsequent operation. For example, high cutting quality may facilitate welding. So, even if the cost of the cutting increases, the cost of the welding may be reduced and the total cost of cutting and welding could be lowered. In a similar manner, a system approach can be broken down into a specific operation. A welding process, for example, should be optimised from both cost and feature aspects. Individual parts of the...
welding system, like the shielding gas, may have a critical effect on the result, but they may have a minor effect on the cost. For example, if productivity can be increased by 20% using a shielding gas that costs 50% more, the total operational cost could still be substantially lower. The simple reason for this is that the cost of the gas only represents about 3% of the total cost. See Figure 1.

Optimised customer solution by the intelligent use of industrial gases

Knowledge of gases and their effect on the cutting or welding process is still limited among users. In welding, knowledge of shielding gases is often restricted to the function of preventing air making contact with the arc and heated metal. This is one function of many. The shielding gas also helps to produce good arc ignition, good arc stability for low spatter levels, good and consistent penetration for reliable results, good mechanical properties and corrosion resistance by controlling the oxidation rate and pick-up of carbon and nitrogen, for example, high-quality and consistent weld surface appearance, as well as low fume and gas emissions. See Figure 2.

The influence of gases is not always simple. In fact, in most cases, it is somewhat complicated. For example, the oxidising component (carbon dioxide and/or oxygen) that exists in some shielding gases is necessary for arc stabilisation. The most suitable amount of oxidising component differs, however, for different materials. The MAG welding of unalloyed or low-alloyed steels requires more oxidising component than the welding of stainless steels. In the MIG welding of aluminium, no oxidising component at all is required for arc stabilisation. An unnecessarily high level of oxidising component, on the other hand, gives rise to unwanted oxidation. This could involve surface oxides but also oxide inclusions. A balance must therefore be struck between enough oxidising component for arc stability and the lowest possible oxidising component to avoid unwanted oxidation. In fact, the oxidising component also has an effect on the surface tension which in turn affects the possible welding speed and the weld appearance. It also has an effect on the burn-off rate of alloying elements which will influence the mechanical properties. As can be seen, the influence of the shielding gas is very complicated. Other gas-related examples include:

- Addition of hydrogen to the shielding gas. In the TIG welding of austenitic stainless steels, this increases penetration and welding speed and thereby productivity. On the other hand, some materials are sensitive to hydrogen because it can be harmful and cause pore formation and even cracking.
- Nitrogen additions can secure corrosion resistance in the TIG welding of duplex stainless steels. In other materials, this does not produce any advantages and might even be harmful by causing porosity or changing material properties.
- The purity level of the cutting oxygen has a strong effect on cutting speed in oxy-fuel cutting. High purity promotes high cutting speeds.

These are a few examples which show that the behaviour of the system often depends on the behaviour of its constituent parts but also on the interaction between the different constituent parts. It is not only the properties of the shielding gas or the filler material or the base material or the power source alone which are important, it is the interaction between them that determines the performance of the system. To complicate things still further, the performance of the system depends on a very large extent on the parameter settings. The optimum performance can only be obtained if all the information is known — that is the properties of the individual parts, their interaction and how they depend on parameter settings. One good example of this is RAPID PROCESSING™. It has made it possible to boost productivity substantially without sacrificing penetration, reliability or weld appearance.

User-friendliness

The working conditions of welders and operators are often demanding, hard, hot, and dirty. Action or equipment that will help welders and operators in their work, to facilitate their work, to improve their health and safety are therefore attracting more and more attention. They can range from the use of more lightweight equipment for easier and more ergonomic handling, or equipment that provides improved reli-
ability by producing fewer irritating interruptions to equipment with built-in knowledge and equipment to improve health and safety.

More gas-related examples include:

- Gas supply systems. A central gas supply system reduces the need to move heavy cylinders. It also increases safety. In case of fire, no or at least fewer cylinders have to be moved away to safer areas.
- Shielding gases that improve the working environment by reducing fume and gas emission.
- Gases that make it easier to set suitable process parameters and help to produce consistent behaviour.
- Gas delivery security. Delivery of a gas to a customer at short notice or within a specified time limit. The distribution form, compressed gas in cylinders or liquids, is less important for the customer as long as the gas is there and has the right quality. The customer pays for a function rather than a component.
- Early warning signals of gas leakage. Leakage that could lead to harmful situations.
- Information booklets that are instructive, like the “Facts about” information series.

**Global environment**

The impact on the global environment of gases in welding and cutting is mainly a result of the production and transportation of the gases. A gas like argon, which is used in shielding gases, comes from the air and returns to the air unchanged. The energy required to separate the small amount of argon that exists in the air (<1%), however, has a negative impact on the environment, as does the energy needed to transport it. The amount of energy that is needed to separate air is minimised in the new and large air-separation plants. Fewer, large plants, however, result in longer transportation. The transportation of liquid argon is comparatively low in terms of energy consumption when compared with the transportation of heavy cylinders containing compressed gas. Efforts are therefore being made to minimise energy consumption in air-separation plants, to use liquid transportation as far as possible and to locate filling stations so that the liquid argon can be put into cylinders as close to the customer as possible. Carbon dioxide is extracted from waste products, mainly from fermentation processes. It is therefore used “a second” time before it is spread in the air.

Some examples of products and applications which already meet future requirements

**MISON® shielding gases**

There are now a variety of MISON® shielding gases for different welding processes, different materials and different purposes. Gases that can improve productivity, contribute to low spatter formation, produce consistent penetration, low surface slag formation and a good surface appearance, as well as improving the welders’ environment by reducing fume and ozone formation.

**RAPID PROCESSING™**

Know-how packages that boost productivity mainly by increasing the deposition rate. No or only small investments in equipment are required. Today there are packages for welding unalloyed and low-alloyed steels, for welding coated steels, for welding stainless steels and for welding aluminium.

**New shielding gas mixtures**

New shielding gas mixtures that optimise the MIG/MAG, TIG and laser welding of “new” materials. Materials that are finding increasing industrial use.

Some examples of “new” materials are duplex stainless steels, martensitic or super-martensitic steels and aluminium alloys.

**AGA LASERLINE™**

A complete range of gases and gas supply systems that produce high performance in laser cutting and in laser welding.
Modern MIG welding power sources

by professor Klas Weman, ESAB Welding Equipment AB, Laxå, Sweden

This article gives a general overview of the technological development of semi-automatic welding machines. When it comes to the state of the art, some modern high-tech equipment is used to exemplify the latest technology.

Welding power sources have been greatly influenced by the rapid developments that have taken place when it comes to power electronic components. The performance of the equipment is also a result of new control and communication technology.

Power sources

The main purpose of the power source is to supply the system with suitable electric power. Furthermore, the performance of the power source is of vital importance to the welding process — the ignition of the arc, the stability of the transfer of the melted electrode material and the amount of spatter that is generated. For this purpose, it is important that the static and dynamic characteristics of the power source are optimised for the welding process.

Different types of power source

Step-adjusted welding rectifier

This is the traditional and still the most common power source for manual MIG/MAG welding. The voltage setting is adjusted by connecting a varying number of windings on the primary side of the transformer. The dynamic

Fig. 1. The new ESAB Aristo 320 and 450 MIG welding equipment.

Fig. 2. Static characteristics of a step-controlled MIG/MAG-welding power source.
properties are set using an inductor. Fig. 2 shows the static characteristics of a step-controlled welding power source. It is important that there are a sufficient number of voltage steps and that they are close enough to enable the welder always to find the optimal voltage setting.

Thyristor-controlled welding rectifier
If the diodes in the secondary rectifier are replaced by thyristors, it is possible to control the output voltage electronically. Unfortunately, the speed of regulation is limited to the frequency of the mains and the dynamic properties must also be mainly controlled by an inductor.

Inverter power source
In the inverter, the mains AC voltage is rectified and transistors are used to produce a higher frequency in the range of 20-100 kHz. This high frequency makes it possible to reduce the size of the transformer. The weight and size of the power source will thus be reduced and the efficiency will be increased. Another major advantage is that a rapid electronic control can be used to control both the static and dynamic properties of the power source.

Traditional and new technology
Electronically-controlled behavior is interesting. Earlier types of power source were designed and built to be optimised for one application or welding method. The new technology makes it possible to use the power source for different methods and to optimise the performance for each application. The function of the machine can be divided into two independent parts — the electronic control and the power package.

The welding properties are no longer determined by the design of the machine but can be controlled electronically or by a computer. The high operating frequency of the inverter power source increases the control speed and makes it possible to achieve optimal properties. It is also possible to use pulsed arc welding where short pulses cut off every single droplet from the electrode. This results in quite new opportunities when welding in aluminium and stainless steel, for example. The freedom to control the machine in different ways makes it possible to use it for different welding methods, but it can also be optimised for each individual choice of electrode diameter, shielding gas and material quality.

Computer technology
As in many other technical areas, the use of computers and computer controls is developing when it comes to welding applications. The more sophisticated the equipment, the more developed the technology — like that used in advanced inverter power sources and control equipment for mechanised welding, for example. Even straightforward standard equipment like power sources and feed units can contain microcomputer controls, something which can in fact be justified from both an economical and service reliability point of view.

Adjusting the equipment
Communication with the user can be facilitated — but perhaps also sometimes made more difficult — by new technology. It should be a challenge for the manufacturers of welding equipment to create a simple and clearly-defined user interface, which still allows all the necessary settings to be made.

Control of the welding process
In order to affect the stability of the arc, inverters include facilities for controlling the welding process. The welding properties are very important to the welder and his acceptance of the power source. As the power source itself does not affect the properties, it is possible to have full control of the process by to have full control of the process by the software. These programs are then independent of the power supply that is used.

Communication between the units
As a result of developments, microcomputers are currently used in many different system components, such as power sources, wire feed units and control boxes. One powerful means of communication between these units is the use of a standard communication bus. ESAB have chosen the CAN bus for this purpose. CAN stands for Controller Area Network and was originally developed for the automotive industry by Bosch and Intel.

In robot welding, the CAN bus is used for communication between the welding equipment and the robot control unit.

Improved immunity to interference
In comparison with the analogue technique, the digital technique is not sensitive to variations caused by voltage drops or other disturbances. This guarantees that the values are reliable and are exactly the same from one occasion to the next. The CAN bus communication between the different parts of the machine, together with an improved mechanical and electrical design (zone system), has also reduced the sensitivity to electrical noise. The CAN bus has the intelligence to re-transmit a message if it has not arrived in the correct way.
**Control box**
The control box, see Fig. 3, is used for all man-machine communication:
- Setting the welding parameters
- Changing the welding method
- Measuring welding data
- Storing parameter settings in the memory

When used for MIG/MAG welding, information about wire type, electrode diameter and gas mixture is specified and the welding properties are optimised for this specific combination. The voltage is pre-set according to a built-in relationship with the wire feed speed, a so-called synergy line. There is a database with more than 175 synergy lines. All you need to do is enter a wire feed speed. A preliminary voltage is then automatically selected by the system.

**PCMCIA card**
A memory PC card (PCMCIA) is used to upgrade the software. The card can also be connected to a PC and be used for storing the library containing the user’s setting data.

The card can store all the welding data that can be moved from machine to machine, thereby maintaining weld quality.

If several machines are programmed with welding data from the same card, the weld result will be exactly the same. This is ideal if several machines are used for welding similar objects.

**Monitoring**
The CAN bus can also be used to monitor the welding process via an external PC. In the Weldoc™ WMS 4000 computer program, the user can supervise the welding process and enter alarm limits. The system is also used for logging and documentation and can be included in the quality control system at a company. This complies with the international quality standard ISO 9000/EN 729.

**Conclusion**
The technological development of electronics and computer technology is rapid and is having a major influence on the development of welding equipment. The information given here can be seen as a teaser about what modern power source technology has to offer.

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