Royal Institute of Technology
Department of Production Engineering

Advanced hybrid manufacturing process for high precision ring of a planetary gear

– main focus on Abrasive Waterjet Machining –

Master of Science Thesis Project in
Production Engineering and Management

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Samanfattning

Under år 2008 uppskattades den totala produktionen av kugghjul inom bilindustrin till 2000 – 2500 miljoner detaljer, varav 1000 - 1400 miljoner av dessa är av hög kvalité [1]. För precisionskugghjul med modul under 1 mm kan tidsbegränsning och kostnader kopplade till design av skärverktyget elimineras genom att tillämpa en flexibel tillverkningsmetod som tillexempel abrasiv vattenskärning (AWJM). Denna studie undersöker designen av ett hybridtillverkningssystem konfigurerat kring AWJM samt föreslår finbearbetningsprocess via konventionella bearbetningsmetoder. Den tekniska möjligheten att producera kuggring av hög precision testas med en 5-axlig vattenjetmaskin och utvärderas enligt kvalitets nivåer för DIN-standard. För detta ändamål studerades ett kugghjul med modul 0,55 mm, 199 tänder, 110 mm i ytterdiameter och 72 mm i innerdiameter samt en tjocklek på 6 mm gjord av Armox T500, höghållfast stål. Resultaten visar på hög potential att uppnå ISO standardkvalité för kugghjul. Vissa kvalitetsegenskaper, definierade i DIN- och ISO-standarder, till exempel ytfinhet med låga värden; Ra 0,8 µm, uppnås vid användning av AWJM. Andra kvalitetskännetecken som profilavvikelse är relaterade till parametrar som skäreffekt, matningshastighet, mängd abrasivmedel, etc. Framtagna värden sträcker sig från Q10 och Q11 enligt DIN3967 vilket möjliggör slutoperationer som till exempel slipning. Geometrisk avvikelse, på ovansidan, gav en maximalt värde på 7 µm med en standardavvikelse på 4 µm. Jetstrålens eftersläpning observerades och kan kompenseras för medan resultatet av rundade hörn existerar i alla skärning med AWJ. Radiell förskjutning, tandtjocklek och index avvikelser visar värden som kan förbättras tillsammans med processoptimering, maskinkalibrering och eliminering av inneboende positionsavvikelser i maskinen. Varje enskild geometri kräver specifika processparametrar och CAM-programmens algoritmer behöver vidare optimeras för arbeten med tämligen små geometrier.

Abstract

Production of gears for the automotive industry during 2008 is estimated to have been between 2000 – 2500 million pieces, from which 1000 to 1400 million pieces were high quality gears [1]. For precision gears with module below 1 mm, the time limitations and costs associated with the design of the cutting tool can be eliminated by using a flexible manufacturing technology such as Abrasive WaterJet Machining (AWJM). This project investigates the design of a hybrid manufacturing system configured by use of AWJM and proposed finishing processes using conventional machining methods. The technical feasibility is analysed to produce high precision ring gears using a 5-axes AWJM system to achieve DIN standards quality levels. For this purpose, a gear with a module of 0.55 mm, 199 teeth and 110 mm in the outer diameter and 130 teeth and 72 mm in the inner diameter with a thickness of 6 mm is studied; the selected material is Armox T500, a high strength steel. The results indicate high potential of producing ISO quality standard gears. Certain quality characteristics defined in DIN and ISO standards, for instance surface roughness – values as low as Ra 0.8 µm, are possible to achieve accurately by using AWJM. Others quality features as profile deviation, are related to parameters as cutting power, feed rate, abrasive feed rate, etc. The displayed values ranged Q10 and Q11 according to DIN3967 which allows for use of further finishing operations such as grinding. The top geometry deviations of a 0.3 mm cut, display a maximum value of 7 µm with an average value of 4 µm. Observed jet lag effects can be improved. Rounded corner effect exists in all AWJ cuts. Runout, tooth thickness and index deviations show values that can be improved together with process optimization, machine calibration and elimination of machine inherent positioning deviations. Each particular geometry needs specific process parameters and CAM software algorithms need further optimization for working with rather small design geometries.

Keywords: Abrasive waterjet machining, AWJM, precision gear, gear manufacturing, Hybrid manufacturing

Acknowledgements

Writing this paper ultimately gave us a unique chance to involve – what we consider to be – the most remarkable figures from Swedish academia, alumni and related industry representatives into the work presented here. Together we proceeded to achieving something that we believe it will lead to a start in further investigation of the field of AWJM. Once again, through continuous effort and common purpose, it has been proved that teamwork gives rise to unimaginable benefits and friendships. Only together we are able to create, otherwise "what we have done for ourselves alone, dies with us; what we have done for others and the world, remains and is immortal" [29].

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Finally, a special gratitude to our families which at the end of the day brought us here and started shaping us to whom we are today, Thank you.

Our warmest thoughts,


Stockholm, July 2016

Table of Contents

Abbreviations

AWJ	**A**brasive **W**ater **J**et
AWJM	**A**brasive **W**ater **J**et **M**achining
CAD	**C**omputer **A**ided **D**esign
CAM	**C**omputer **A**ided **M**anufacturing
CMM	**C**oordinate **M**easuring **M**achine
CNC	**C**omputer **N**umeric **C**ontrol
DIN	**D**eutsches **I**nstitut für **N**ormung (German Institute of Standardization)
HAZ	**H**eat **A**ffected **Z**one
HBW	**B**rinell **H**ardness
HI/LO	**HI**gh / **LO**w
HV	**V**ickers **H**ardness
ISO	**I**nternational **S**tandardization **O**rganization
NC	**N**umeric **C**ontrol
TAC	**T**aper **A**ngle **C**ontrol

1 Introduction

This section presents a brief background regarding gear manufacturing and abrasive waterjet machining, the scope and aim, as well as the research questions that motivate this investigation and the delimitations of the project.

1.1 Background

In 2008, 60 million cars were produced worldwide; and 5 to 6 million in Germany alone. The production of gears was in the range of 2000 to 2500 million pieces worldwide, and approximately 10% of was produced in Germany, from which 120 to 140 million were high quality gears; generating a turnover of eight to twelve Billion Euros. These figures highlight the relevance of the gear production industry, for both power transmission and steering system [1].

Gear production can be achieved by conventional metal processing techniques, which are those techniques that have already achieved a mature state, such as machining, forging, stamping or casting; out of these methods, the most common manufacturing method is machining. Machining of gears can be divided in two subcategories: 1) Gear generating, and 2) Gear form-cutting. Hobbing fall into the category of gear generating; while milling is considered gear form-cutting process [2].

As in any other metal forming processes, gear manufacturing presents several problems and disadvantages like undesirable heat treatment, residual stresses, high dynamic forces, vibrations, tool wear, etc. These disadvantages can be address by changing the conventional manufacturing method with modern technology as is Abrasive Waterjet Machining (AWJM). With AWJM there are low cutting forces compared to machining, negligible heat generation in the cutting region and high flexibility since there is no need for specialized tools to manufacture different components.

1.2 Scope and Aim

The scope of this thesis project was to develop a hybrid manufacturing system for high precision gears, which involves Abrasive Waterjet Technology and a conventional finishing operation. Conventional manufacturing methods to produce gears usually involve the design and use of specialized tools for each specific gear, resulting in high cost and long lead times. Since nowadays the market has become more and more competitive, the need for custom made products and short delivery times, a need for flexible manufacturing approaches has risen.

The principal objective of this project was to determine the technical feasibility to change the current production methods, to more technological advanced ones that allow higher flexibility, but at the same time is capable to reach required quality standards in the industry, determine by national and international standards. The technical feasibility will be determined according to the best quality that can be achieved using AWJ. The quality will be determined according to international standards using parameters such as surface roughness and dimensional accuracy.

1.3 Research Questions

- Is it possible to produce precision gears using abrasive waterjet machining, and if so up to what quality level according to DIN3967?
- What kind of hybrid technology can be implemented to enhance abrasive waterjet machining to produce precision gears?
- What are the potential benefits if the automotive industry changes the current gear manufacturing method to a more flexible and environmental friendly method?

1.4 Delimitation

The present project is focused on determining the best quality that can be achieved using AWJM and in the investigation of conventional methods that could be used to provide a finishing process to correct the geometry after AWJM, creating a hybrid approach.

The CAM software use in this project is IGEMS 2015.

For further simplification of the term “high precision ring gear”, the term “gear A” will be used through the thesis when referring to the investigated high precision ring gear.

In order to compare the technical feasibility to produce a high precision ring gear, a part machined with conventional methods is provided with the following characteristics in terms of material:

Table 1. Characteristics of gear A

Chemical composition	30CrMoV9
Hardness	750 HV

However, the above mentioned material hardness is given in a nitriding hardening process on a depth of 0.1 mm, according to design specification sheet.

The gear that is been studied is a spur ring gear. The selected material for this case is one with similar thorough hardness described in Table 1; this was of importance since it is common in the industry that gears are heat treated to achieve a high hardness in order to extend life and reduce risk of failure for wear. The main characteristics of the gear are:

Table 2. Characteristics of gear A

Material	Armox 500T
External module	0.55 mm
Internal module	0.55 mm
Thickness	6 mm
Hardness	480 – 540 HBW
External teeth	199 teeth
Internal teeth	130 teeth

The machine tool selected to perform the experiments was a FineCut WMC 500 II, which is a 5-axes fully enclosed micro waterjet cutting machine, using a 37 kw, 4000 bar pump. The abrasive used is Barton Garnet HPX 230.

Due to high number of parameters defining a gear, a restriction has been made when investigating the quality features of gears. Therefore, the following parameters were investigated:

- Tooth thickness
- Profile
- Index
- Runout
- Surface roughness
- Hardness

The standards that are being used as reference to determine the potential quality that can be achieved are: Standards: DIN3967, DIN3967/25, ISO 1328-1, ISO 10064-2 and DIN 867.

Due to the lack of specialized equipment for measuring gear quality features e.g. gear measuring centres as Klingelnberg P26, an optical method was adopted to carry out measurements and determine the quality of the gears. Considering the optical deformations and contrast method used in this measurement, the digits after the decimal point should be taken cautiously.

2 Theoretical framework

This chapter presents relevant information to analyse gears and what is to be measured in order to ensure specific quality level, according to international standards. In addition, a state-of-the-art literature review regarding AWJM is presented.

2.1 Overview on gears

Gears are present as parts in various rotating mechanisms which are generally used to transmit power from one part of a machine to another. The rotating transmission systems also include linear parts such as racks and due to their configuration parameters as torque, speed and direction of the power source may be changed [3].

Currently gears are classified according to their use and manufactured geometry as:

- internal/external
- shape (e.g. spur, bevel, helical, worm gear)

There is a large number of gear types, nevertheless gears are subject to specific usage and proprietary design, hence new types of gears might be encountered in literature or industry. This is the case of our studied gear also.

A significant amount of characteristics describes a gear, see Figure 1 for a graphical representation, such as:

- Circular pitch
- Module
- Diametral pitch
- Addendum
- Tooth thickness
- Etc.

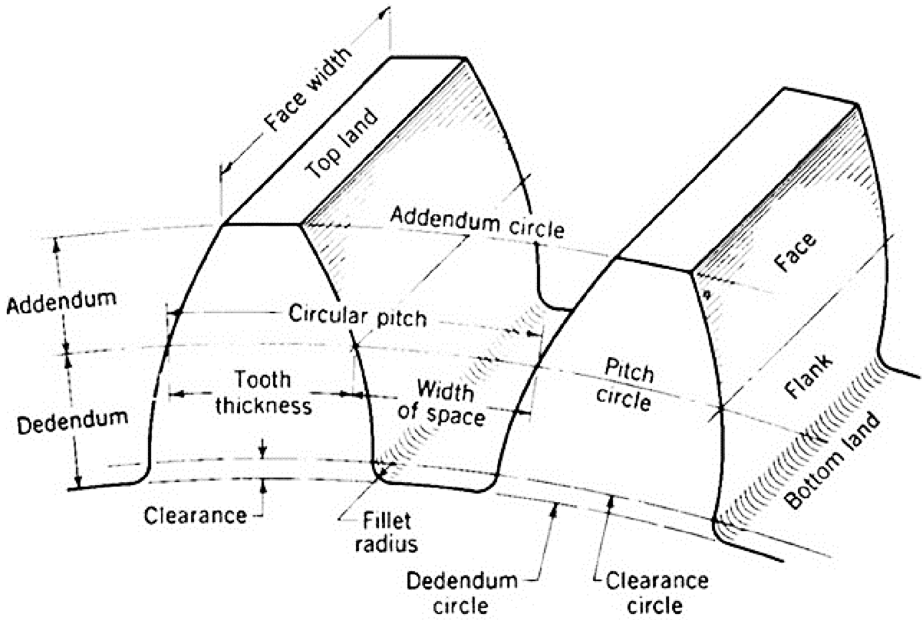


Figure 1. Gear nomenclature

Further on, focus is on a rather simple gear:

A Spur Gear is the simplest type of gear, the teeth are parallel to the axis of rotation and can be used to transmit motion between parallel shafts.

Figure 2. Spur gear

Given that every gear type must comply to a quality standard, whether this is an internal or external one, the following characteristics are to be initially measured:

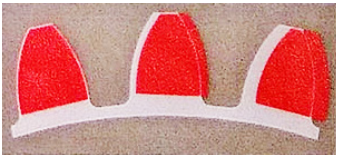
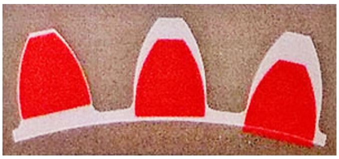
The tooth thickness is the length of the circular arc between two tooth flanks of a tooth on a pitch circle in the transverse plane	Tooth thickness: 
The profile parameters should be measured perpendicular to the involute and describe the position and form of the influence of other parameters	Profile: 
The index parameters are measured at the midpoint of the tooth height and describe the position of all right flanks or all left flanks relative to each other	Index: 
The runout describes the radial position of all the teeth on the pitch circle	Runout: 

Figure 3. Quality features of gears

There is a continuous trend in the industry for improvement in gear capacity in terms of load, weight, size, cost and lead time. Since gears are mostly used to transmit power and motion transmission, a considerable amount of time and effort is put into developing new methods that enables in improvement in load carrying capacity of gear teeth [5].

The load carrying capacity of gear teeth is determined by two main factors, the mechanical properties of the material of which the gear is made from, and the geometry of the teeth themselves. Among the mechanical properties affecting this property we can find the tensile strength, surface defects, notch sensitivity, mean stress sensitivity, etc. From the side of the teeth geometry, some of the factors that influence the strength and load capacity we can find pressure angle, modulus, geometry deviations, contact ratio, application of the gear, etc.

Some of the most commons failure modes in gears are produced by fatigue or wear; fatigue in a material is the weakening due to constant loading and unloading. The bigger stresses on gears are produced in the tooth root, therefore an improvement in the tooth root geometry will result in an improvement in tooth root load capacity [5].

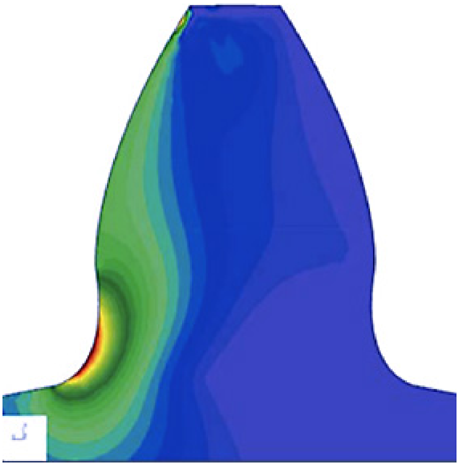


Figure 4. Stresses in tooth root [4]

Brecher *et al.* [5] developed a method to evaluate and optimize tooth root load capacity using a finite element method to simulate and evaluate operational behaviour. Three methods are presented to evaluate the root stress by modifying the root design geometry. The first one method consists of parameterizing the tooth geometry and modify the root using ellipses to generate a new geometry. The second method uses the same approach but instead of ellipses, tangent functions are used to generate the new root. Finally, the third method consist in the creation of vectors that fit within a circle, that describe the tooth root fillet, then the point of contact is moved along the vector lines to generate the new geometry. The evaluation of stress in tooth root geometry after applying geometry optimization showed a reduction of at least 15% compared to the stresses present in a root with design geometry.

2.1.1 Standards

Standards are documents that aim to provide requirements, specifications, guidelines and characteristics to follow in order to ensure products, materials, processes and services quality to a certain level. Some of the benefits that standards offer to those who choose to use them is to prove that products and services are safe and reliable; in addition, standards provide tools to increase productivity, become internationally competitive, reduce waste and, since it includes state of the art technology, reach for new markets [25].

ISO is an international, non-governmental organization with members of 161 nations; while DIN is private non-profitable organization that provide standardization services, it is recognized by the Federal German Government as the standardization body that represent Germany interest in European and international level [26].

Regarding gear quality, there are several standards that provide guidance in order to ensure quality in different parameters of gears, for instance: tooth thickness allowance, backlash assessment, profile deviation, helix trace, etc. Due to the limitations in equipment to conduct measurements according to ISO or DIN standard methods, specific parameters that can be measured with alternative methods that provide an overview of the quality that can achieved during experimentation were selected.

In the **ISO 1328-1 Cylindrical gears - ISO system of accuracy-** Single pitch deviation is defined as: "algebraic difference between the actual pitch and the corresponding theoretical pitch in the transverse plane, defined on a circle concentric with the gear axis at approximately mid-depth of the tooth". For gear with a reference diameter between 50 and 125 mm, and module between 0.5 and 2 mm, the accuracy grades range from Q0=0.9 μm to Q12=61.0 μm. The general quality of a specific gear feature is given by the worst obtained quality value Qx (where Qx is ranging Q0-Q12).

2.1.2 Conventional production methods for gears

Nowadays, there are several methods to produce gears thanks to the technological advances to work with metallic elements. Nevertheless, the most prominent one is machining. Within gear machining, we can define two different categories: 1) Gear generating and 2) gear form-cutting.

2.1.2.1 Gear generating

Gear generating is the process to produce a gear by a relative motion between the cutting tool and the workpiece; the most used generating process is gear hobbing [2].

Gear hobbing is the process of manufacturing a gear using a cutting tool named hob, which is a helically teeth cutting tool. The process employs a relative motion between the hob and the workpiece. The hob and the workpiece are mounted in two separate spindles that rotate at a determine ratio depending on the parameters of the desired gear; the angle between the two shafts is determined by the angle of the teeth in the hob and the type of gear that is being produced, for example, if a spur gear is being produced, the angle between the shafts must be equal to the angle of the teeth in the hob. The relative motion of the shafts is determined by the number of teeth of the gear, for instance, if the gear is to have 30 teeth the ratio should be 30:1, meaning that the hob shaft should do 30 turn for each turn of the workpiece shaft.

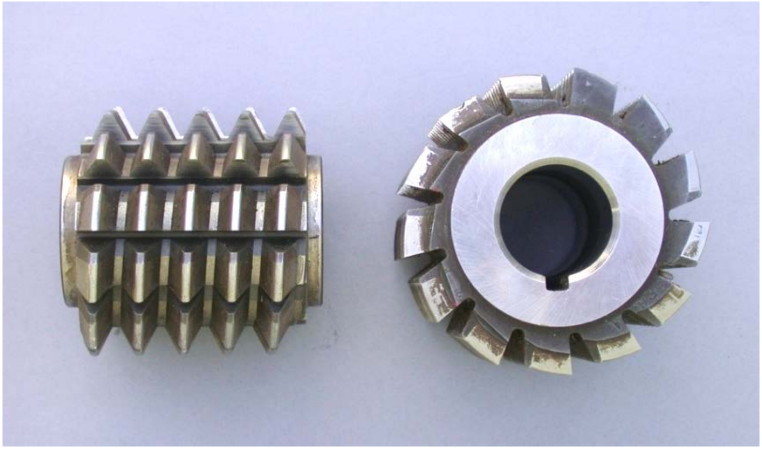


Figure 5. Hob

2.1.2.2 Gear form-cutting

On the other hand, gear form-cutting is the process where the cutting tool has the desired geometry or profile of the gear; the two most use form-cutting processes are milling and broaching [2].

Milling is the conventional process of machining that uses a relative motion between a multi-edge cutting tool, and a fix workpiece.

Broaching is a metal cutting technique that uses a cutting tool with multiple edges, called the broach; one edge is larger than the previous one, until the last cutting edge has the final desired geometry. The cutting motion is carried out by the tool, and the material is removed in one single stroke, either by pushing or pulling, in a pre-machined operation in the workpiece. In the case that the workpiece is mounted in a lathe, the broach must rotate at the same speed as the workpiece [6].

2.2 Abrasive Waterjet Machining

Abrasive Waterjet Machining is a nonconventional machining method that converts the potential energy of high pressured water into kinetic energy, and with the help of an abrasive material, it erodes the workpiece material. One of the most important characteristics of this method is the possibility to machine virtually any type of material [7].

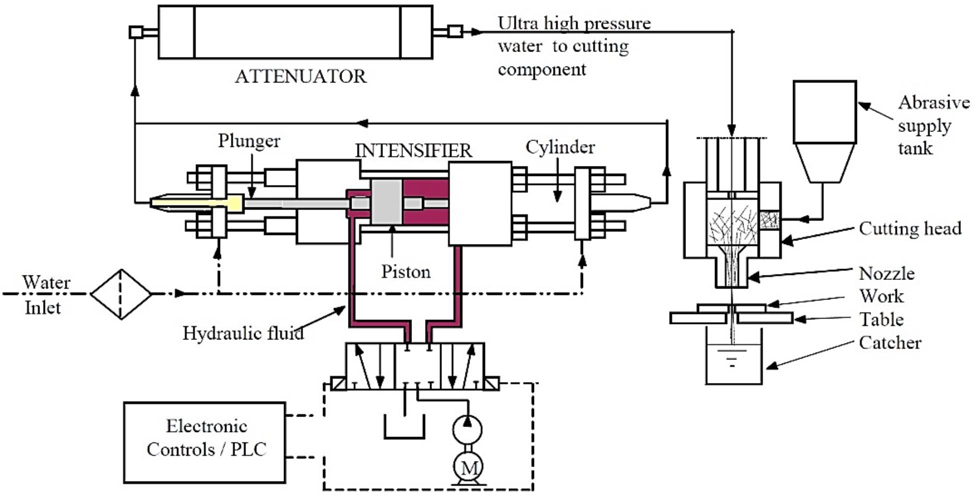


Figure 6. Schematic of AWJM system [8]

This technology is used in a variety of industries that ranges from food industry to aerospace, and even in the medical industry [9]. From the automotive industry the most prominent case is the BMW i3, which is the first volume production vehicle that uses AWJM to machine parts of the body due to the fact that this method produces almost no deflections, making it is suitable for flexible materials, such as carbon fibber-reinforced polymer used in the BMW i3.

As mentioned before, one of the principal advantages of AWJM over other machining methods is the possibility to machine a wide number of materials, such as plastics, fabrics, rubber, wood products, paper, leather, insulating materials, brick, composite materials. In addition, the cut can be started at any location in the workpiece without the need of a pre-drilling operation, no thermal distortion, low cutting forces are generated, making this method suitable for flexible material that are difficult to clamp, and it is an environmentally friendly method.

There are different types of abrasives that are commonly used in AWJ, some of the most used ones are garnet, olivine, aluminium oxide, glass beads, silicon carbide, silica, zirconia, etc. However, despite the number of abrasives available in the market, the most popular abrasive for AWJ equipment users is garnet.

Garnet is a mineral that comes in the form of crushed angular particles or round shaped particles. It is the most used abrasive for AWJM. Barton Garnet HPX is the abrasive used in this thesis project and present the following technical data:

Table 3. Technical Data Barton Garnet HPX

Physical properties		**Chemical composition**	
Color	Red - pink	SiO_2	41.34 %
Shape	Sharp angular crystals	Al_2O_3	20.35 %
Specific gravity	3.9 - 4.1	Fe_2O_3	12.50 %
Hardness	8 - 9 Mohs	MgO	12.35 %
Melting point	1 315 °C	FeO	9.70 %
Mesh size	50, 80, 120, 150, 220	MnO	0.85 %
		CaO	2.95 %

2.2.1 Quality in AWJ

The results that can be obtained in AWJM depend on several parameters that can be control during the process. The surface roughness and the geometry accuracy that can be obtained are mainly restricted by the water pressure, feed rate, standoff distance, abrasive flow rate, abrasive mesh size and orifice and nozzle diameter [7].

Figure 7. AWJ main parameters

2.2.1.1 Kerf Taper

Due to the nature of AWJM, the process is not yet fully optimized and thus present disadvantages and challenges. The performance of this process can be evaluated in terms of cutting depth, material removal rate, cut surface topography and kerf geometry; being kerf geometry of great importance.

Kerf taper is characterized by a difference in width at the entry and exit point in the workpiece as illustrated in Figure 8 [10].

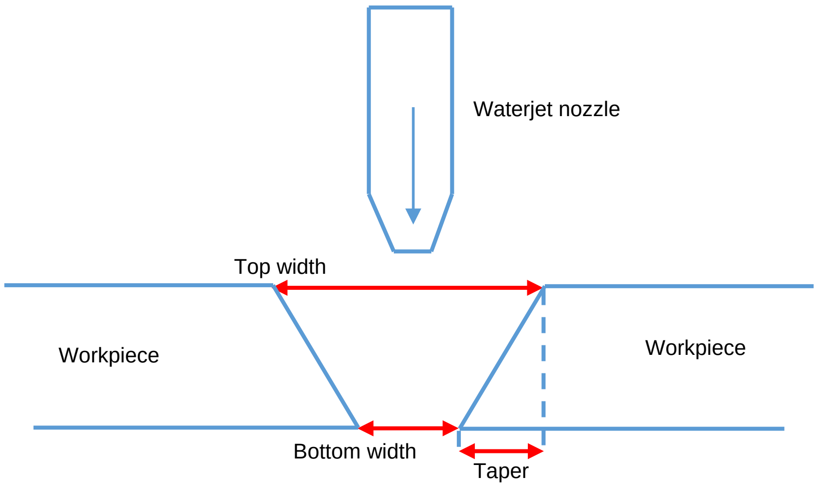


Figure 8. Kerf taper

The principal parameter affecting the kerf width are traverse speed and standoff distance. Research has shown that in order to minimize the kerf taper angle it is suitable to reduce the traverse speed. In multi-pass machining, using the same traverse speed, it has been detected a reduction in kerf width of approximately 27% in comparison to single-pass machining; consequently, multi-pass machining is recommended for thick materials [11]. However, this solution is not used in practices since it reduces the material removal rate and increase the process costs of production [12].

Regarding standoff distance, research has shown that increase in standoff distance results in an increment in top kerf width and a reduction in bottom kerf width.

The most prominent solution to this problem is the use of multi axis machines to use a kerf taper compensation technique. The solutions proposed by this technique is to tilt the nozzle at an angle, normal to the traverse direction, as shown in Figure 9.

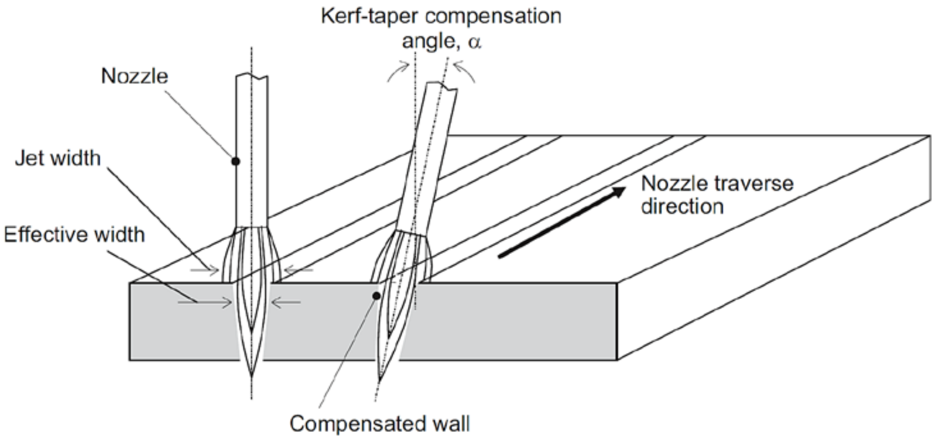


Figure 9. Kerf taper compensation [12]

2.2.1.2 Surface roughness in AWJ

A machined surface texture can be described by three topological components: waviness, roughness and error of form. In manufacturing parts, the surfaces roughness is one of the principal quality aspects [13]. In the AWJ machined surfaces it is possible observe three different zones along the cutting walls: the initial damage region, smooth cutting region and the rough cutting region. The initial damage region shows a low surface roughness cut; the smooth cutting region presents a uniform smooth and the surface texture is primarily defined by the abrasive particle size; and the rough cutting region is affected by the parameters that influence the kinetic energy of the jet and present large surface striations as result of particles impacting the material at large angles, producing poor surface roughness [14],[15].

The parameter that present a more significant contribution to the variation in surface roughness are water pressure, traverse speed, abrasive flow rate and abrasive grain size.

Water pressure influence is more notorious in the rough cutting region; the increase in velocity of the abrasive particles cause a positive effect in the surface roughness, however high pressure can also result in negative effects since the abrasive particles loose cutting ability if they became too fragmented [13].

The jet traverse speed presents a similar behaviour to water pressure. An increase in traverse speed results in poor surface roughness quality, while the best surface roughness is obtained at low traverse speed. Traverse speed shows small influence in the initial damage region and the smooth cutting region. It is important to keep in mind that low traverse speed may result in a change in the taper angle, which can be used to eliminate the angle or increase it [13].

An increase in abrasive flow rate can result in an improvement in surface quality, but these phenomenon is related to the depth of cut and is given by the ratio between abrasive and water mass flow rate, hence can been seen in the following equation:

$$h \; \alpha \; r/(1+r)^2 \qquad Eq.\ 1$$

Where h is the depth of cut and r is the ratio of abrasive and water mass flow rate [16]. However, it is important to mention that if the optimum value of abrasive flow rate is exceeded, it will result in a decrease in surface quality since the collision between abrasive particles will decrease the exit velocity and therefore the cutting efficiency [13].

Regarding the abrasive grain size, it has been proven that a reduction in the grain diameter, which mean increase in grit size, will result in a better quality surface. Nonetheless, if the thickness of the material increase while the abrasive particle size is reduced, the surface quality will reduce drastically since the abrasive particles will reduce its inertia. In order to solve this phenomena, water pressure can be increased to achieve a higher particle velocity.

In addition to the aspects mentioned before, striation marks are another characteristic that is present in AWJ machined surfaces. These striations marks are present in the cut surface with direction perpendicular to the feed rate direction, and are mainly dependent on the jet power and cutting velocity, Figure 10. Some of the possible explanations for the formation of these striations found in literature are [17]:

- Oscillating movement of the jet
- Vibrations during cutting process
- Variation in the distribution of kinetic energy in the abrasive grains inside the jet
- Decrease in kinetic energy as the depth of cut increases

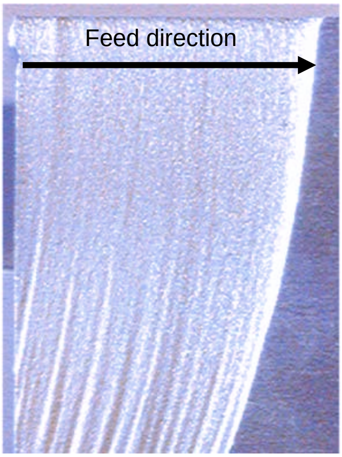


Figure 10. Striation marks formation [17]

2.2.1.3 Environmental impact and benefits of AWJM

AWJM presents a number of sizeable advantages, mainly expressed by:

- Possibility to cut hardened material
- Chunks of metal VS. Chips with oils
- Flexibility to change design
- Higher utilization for prototyping
- Water may be drained directly in the sewage

- Abrasive can be reused
- No HAZ

By having the possibility to cut hardened material, in specific applications where hardening is an in-house process this can be of advantage as it will skip the hardening times which are higher as the hardened depth increases.

For achieving cleaner cuts, especially in rather soft composite materials, SUPER-WATER® [28] can be used. This is a concentrated industrial water blasting additive added to the water, in order to increase the water jet focus and increase cutting speed to produce a cleaner cut.

2.3 Finishing processes

There are several finishing processes that can be used in order to achieve national and international standards quality. Most of these processes include the utilization of highly specialized and complex tools that are able to produce thigh tolerances, in addition to the complexity of each process itself.

Relevant processes that can be used for manufacturing gears are presented.

2.3.1 Grinding

Grinding is a metal cutting technique that uses a multi-edge cutting tool, which is the one carrying the cutting motion, to remove material from the workpiece; one of the principal characteristics of the cutting tool is that the cutting edges are not geometrically defined. Grinding can be categorized into two classes depending on the configuration of the cutting grains: 1) bonded, ex. Grinding wheel, grinding belt, honing stone, grinding worm; and 2) loose, ex. Lapping [6].

Discontinuous profile grinding is a process commonly used to achieve dimensional accuracy and high surface finish quality in gear, especially in spurs gears [1]. The process consists in the utilization of a grinding wheel with a cutting edge capable to access either one or two flanks in a gear, and with a CNC machine move the grinding wheel to achieve the desired geometry.

Continuous profile grinding is performed by cylindrical grinding worms; the profile of this grinding worms match to a rack, or linear gear, and is by relative motion of the workpiece and the tool that the cutting processes is performed. One of the advantages present in this method is that the profile of the grinding worm depends only on the module and pressure angle of the gear that is to be produced; thus one grinding worm can be used for multiple gears sharing module and pressure angle.

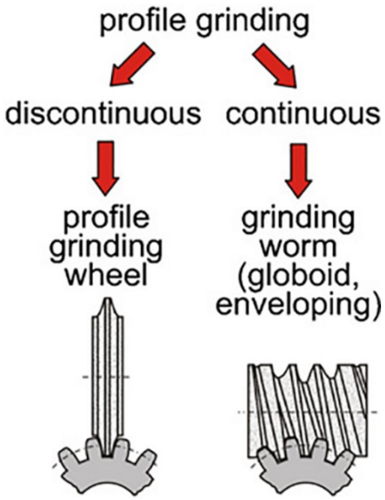


Figure 11. Profile grinding [1]

As the grinding process is performed, the cutting tool is affected by wear and the accuracy is then decreased or lost. One solution to correct this problem is profile dressing, which consists on using a dressing tool, a natural diamond or polycrystalline diamond, to reshape the grinding tool to the desired profile geometry. For discontinuous profile grinding a single dressing disk is used while the grinding wheel rotates and is moved, by a CNC machine. Whereas in continuous profile grinding, a form roller is used to correct the tool in a process where the rotational speed and feed rate are synchronized depending on the pitch [18]. Cubic Boron Nitride (CBN) is the most common material used for vitreous grinding wheels, which are dressable.

2.3.2 Micro-milling

Milling is a metal cutting process that involves a multi-edge cutting tool. During the machining process the tool is connected to the machine tool spindle, providing the cutting motion, and is the workpiece the one that perform the feed motion. The milling process is divided in two approaches depending on the relative motion between the cutting tool and the direction of the feed rate; Up milling is the process in which the tool rotates in a direction opposite to the feed rate of the workpiece, while in Down milling the rotation of the tool is in the same direction as the feed rate [6].

Micro-milling uses the same principle as milling, with the difference that the cutting tool has a significantly smaller shank diameter. This method is used when small complex features are necessary and a high surface finish is required. The main issues of micro-milling are that since the milling tool has a small diameter, it offers small resistance to deflection, resulting in deformation of the tool. This deformation of the tool creates a problem to control the actual position of the tool compared to the theoretical one, resulting in geometrical inaccuracies of the workpiece [19].

Surface roughness has been proved to be stochastic in micro-milling as a result of the uncertainties in the process; this stochastic behaviour is directly related to the tool diameter, and as the tool diameter decreases, the surface roughness quality decreases. Furthermore, while machining stainless steel the produced chips are powder-like, and get rubbed into the surface, producing an even more damage surface finishing [20]. Oliaei et al. were able to achieve an areal surface roughness (Sa) of 0.4 µm in a circular pocket on Stavax stainless steel.

2.3.3 Wire EDM

Wire Electrical Discharge Machining (Wire EDM) is considered a non-conventional machining processes since it erodes the material in the workpiece, instead of cutting like in milling, turning, drilling, etc. The process uses a wire that travels in a predefined path cutting the material of the workpiece through a spark discharge, with the assistance of a dielectric fluid that can be a mineral oil or kerosene.

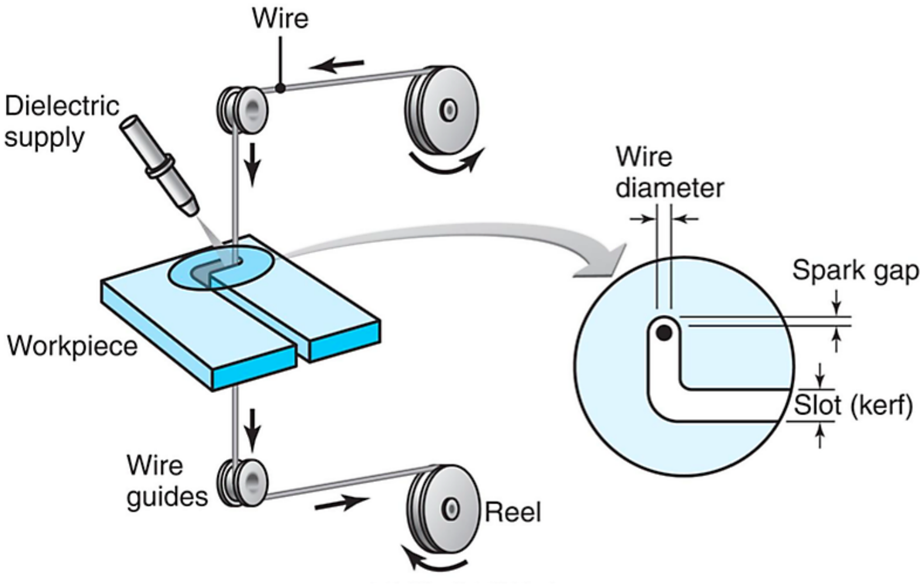


Figure 12. Wire EDM

The principal characteristics of the wire used in this processes include: the wire is used only once, the price is relatively low for the type of applications it can be used in, the typical materials are tungsten, brass, copper or molybdenum, travels at a constant speed, the wire maintain a constant kerf during the cut.

Compared to conventional machining methods, researched has shown that wire EDM can achieve a higher dimensional accuracy and smooth surface roughness. It has been proved that wire EDM is capable to obtain surface roughness average Ra in the order of 3-4 μm during the main cut of Inconel 718 [21]. In addition, if a subsequent trim cuts are performed in the same material, it is possible to achieve a surface roughness of 0.21 μm.

However, due to the nature of the process, the high temperatures that can reach 40,000 K, there is considerable impact in surface integrity in terms of surface topography, microstructure change, micro-hardness and residual stress. The heat affected zone is characterized by a white layer which is related to residual stress, micro-cracks, grain wroth, porosity and alloying from the tool and electrode or dielectric fluid. Nevertheless, it has been proven that the white layer can be improved by controlling the processes parameter and the generators used in the process. Furthermore, with multi-pass cuts it is also possible to remove the white layer.

2.3.4 Broaching

Broaching is a cutting metal technology that uses a multi-edge tool, called broach, which is the one carrying the cutting motion. In this method, there is no tool feed rate since the tool perform the cut in a linear direction against the workpiece surface. Broaching can be done linear or rotary; where linear broaching is performed in a broaching machine and rotary broaching is typically performed in a lathe.

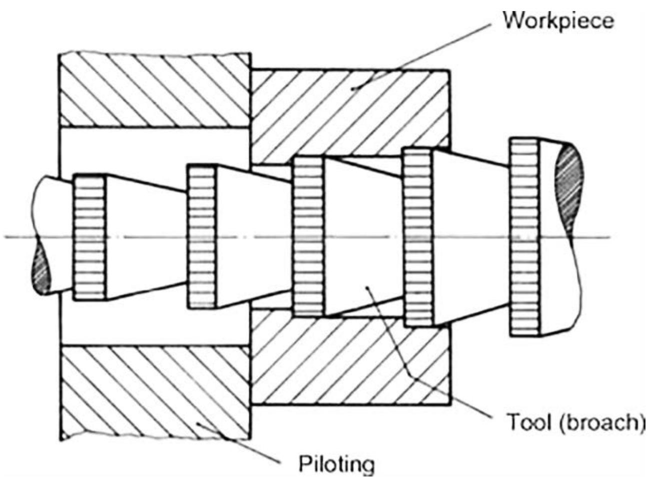


Figure 13. Broaching [6]

The material removal is done in one single stroke by the broach; which cutting edges are increasing in diameter or shape. This process can be performed in two procedures, internal and external. For internal broaching, the tool is brought to a pre-machined opening and pushed or pulled, until the last cutting edge pass by the opening generating the final geometry. External broaching, is used to produce external profiles or features that are difficult to produce using other machining processes like turning or milling; one of the most common applications for external broaching is teeth and guiding surfaces.

One of the main advantages of broaching, and the principal reason for use this machining method, is the high level of accuracy that can be obtained in shape and size. Broaching is an economical procedure in terms of geometry complexity and that there is no need for a post process operation to achieve a good surface quality. Surface quality of mild steels can be achieved in the range of: R_t = 6.3 to 25 µm; however, this value can be improve for casting steels and with a higher control of vibrations during machining operation [6].

2.3.5 Power Skiving

Gear power skiving is a machining process used to manufacture mainly internal gears. This process is different from hobbing since the skiving tool is mounted in a cross axis angle relative to the gear to be produced, similar to gear shaving. The cutting process is initiated by the relative motion between the tool and the workpiece, generating a continuous chip formation. The skiving tool is positioned tangentially, to the lower point of the pitch circle, using as reference the pitch circle of both the tool and the gear. The direction of the cut for a spur gear is parallel to the axial direction of the gear [22].

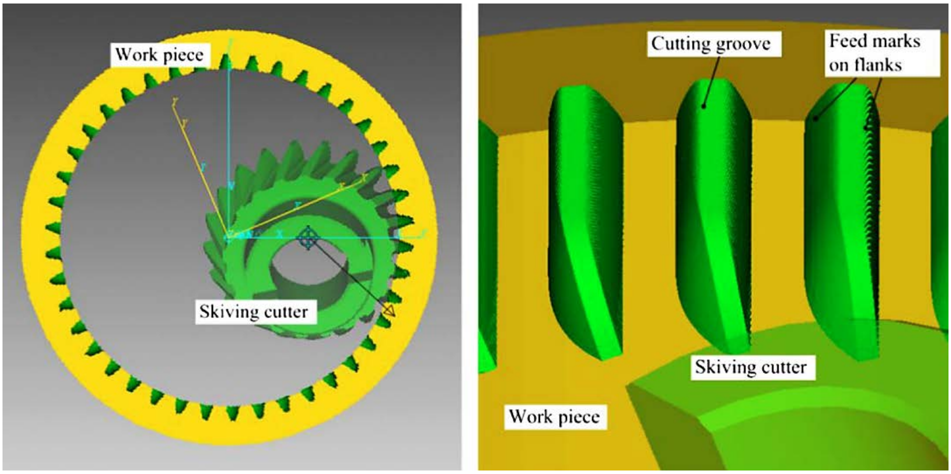


Figure 14. Power skiving [22]

It has been proved, by previous research, that power skiving of internal gears is several times faster than shaping, and is a more flexible method compared to broaching, as a result of the continuous chip formation capacity. Skiving was first patented in the beginning of the 20th century; however, power skiving always encountered technological difficulties regarding machine tool technology and cutting tools. Recent developments in the field of numerical control of direct drive spindles, geometry tool optimization and tool coating technologies, recent research make evident that power skiving is a high productive and flexible manufacturing method for internal gears [22].

2.4 Hybrid manufacturing

Today's constant industrial and technological evolution has led to create a need for manufacturing and machining systems that are capable to produce complex parts, work with enhanced materials, reduced lead time, and improved quality. One approach to solve this situation is the development of hybrid manufacturing systems. These systems present several advantages over conventional ones, for instance higher machinability, reduction in cutting forces, increase in tool life, improvement in surface integrity, etc [23].

Hybrid manufacturing is a large field, and as such, there are different approaches that can be taken into developing a manufacturing system that can be considered hybrid. Schuh et al. have defined several definitions for hybrid systems: a system that involves simultaneous use and control of multiple mechanisms and energy sources at the same time in the same zone, e.g. laser assisted turning and milling; hybrid manufacturing can also be the of process steps that are usually performed in separate steps; hybrid machines are those that combine different machining processes within the same machine, e.g. turning-milling machines [27]. Furthermore, it can be considered a hybrid machining processes the one that, by combining different technologies used to remove material, is capable to change the processes planning in order to improve and make more efficient the production.

In general, hybrid manufacturing processes can be categorized in two different classes. The first one is the assisted hybrid processes, where one of the involved processes is used to facilitate or enhance the capabilities of the second one. The second category is the mixed or combined processes, where the methods involved are both actively contributing to material removal, complementing each other to achieve the desired result.

3 Methodology

This chapter provides a detailed explanation of the methodology followed during the experimentation phase of the project.

3.1 Experiment description

The experiments performed in this project are conducted using a fully enclosed 5-axes FineCut WMC 500 II, with a working envelope of 500 mm x 500 mm x 50 mm, in X, Y and Z axes and a range of ±15° for A and B axes. Stated machine accuracy of 1 µm.

The FineCut WMC 500 II AWJ machine is capable of cutting materials with a positional accuracy of 1 micron and use variable water pressures (2 values, HI/LO) through the cut process. However, these factors are influenced by properties in the material to be cut and parameters of AWJ machine.

In addition to the studied gear A, a new Gear B is designed and scaled 10X gear A module on the same diameter; outer teeth exclusively. This is done to better compare the results between small and large geometric features. Gear B deign results in a number of 18 teeth and has the same material properties as the investigated gear A.

Initially, to compare the behaviour of different sizes in orifices and nozzles, cuts are performed using a representative portion of a gear that consist of 10 teeth. Once that a pair orifice-nozzle was selected, a cut of a full gear A is made. Micro-joints, which provide material bridges between Armox plate and the gear being cut, are used instead of fixtures in two points of the addendum circle. After an initial examination and measurement on the bottom geometry cut, it has been observed that for every inside corner (root circle area of gear A) cut with the AWJ system, there is presence of a systematically deformed geometry. In an attempt to correct the geometry, feed rates as low as 2 mm/min were used. The controller uses an algorithm for interpolation of speed which is done in steps, instead of smooth continuous speed change. It was considered that due to the small geometry features of gear A, interpolation may not work as intended due to its initial design of working with rather larger geometries. Further on, it has been assumed that a larger distance between two teeth would allow the water jet speed to be corrected by the machine controller, resulting in an improved bottom geometry.

In order to validate the assumption and detect the cause of the incorrect geometry present in the undercut area (distance between two teeth on the root circle) of Gear A, a cut on Gear B has been made. An initial measurement revealed that the same incorrect geometry is generated on the gear B cut; the feed rate is lowered again. The results on gear B are compared (Figure 22, 23).

Figure 15 exemplifies the regions of a gear tooth. The same terms are further used in this thesis.

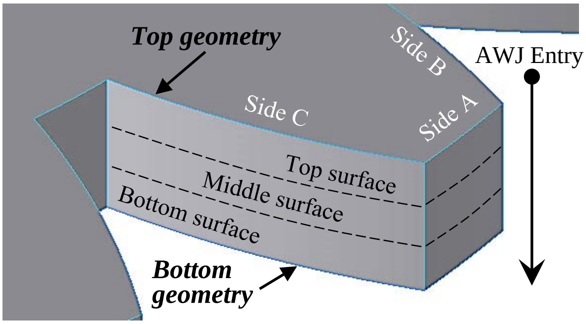


Figure 15. Illustration of tooth regions

Figure 16 exemplifies a displacement between a virtual water jet perpendicular position to a cut surface and the real water jet position and distortion during a straight cut. The displacement obtained due to the water jet bouncing back at its impact with target material is called jet lag.

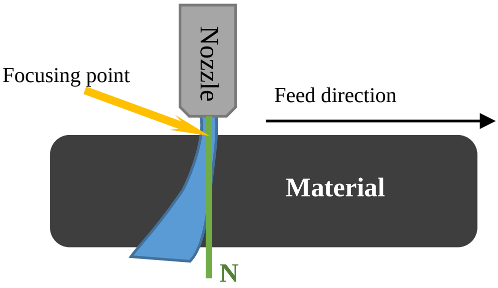


Figure 16. Straight AWJ cut section. Blue represents waterjet, green N line is the virtual position of the waterjet, normal to the cut surface. The displacement between the blue and green line represents jet lag in relation to mentioned feed direction

3.1.1 Cutting parameters definition

In order to determine the optimal parameters on the studied material and desired geometry experimental cuts were made using different sapphire orifice and nozzle diameters available. Pairs of orifice-nozzle are selected as follows:

Table 4. Pairs of orifice-nozzle

Orifice	Nozzle
0.08 mm	0.2 mm
0.10 mm	0.2 mm
0.12 mm	0.3 mm
0.17 mm	0.3 mm
0.17 mm	0.4 mm
0.17 mm	0.5 mm

The selection of the pairs is based in the information found during the literature review phase of the project, where ratios in the range of 1:3 up to 1:4.5 are suggested [10]; as well as in the recommendations from the manufacturer of the machine Finepart that commonly uses ratio of 1:1.5 and 1:3.

Water pressure is used fixed at 3800 bar throughout all the experiments.

Standoff distance is set to two times the diameter of the chosen nozzle for each experiment. This value has been agreed with the equipment manufacturer for achieving a correct focus point (Figure 16) of the waterjet. Positioning the focus point at the correct standoff distance ensures that the geometry is cut according to the generated tool path.

The selection of abrasive feed rate is related to the nozzle diameter and is based in the recommended values from Finepart, being those values the following:

Table 5. Abrasive feed rate values

Nozzle diameter	Abrasive feed rate
0.2 mm	20 gr/min
0.3 mm	30 gr/min
0.4 mm	50 gr/min
0.5 mm	60 gr/min

The feed rate, or traverse speed, was initially selected according to the default values provided at IGEMS for the X-fine for a plate of mild steel with a thickness of 6 mm, with maximum value of 70 mm/min for a 0.5 mm nozzle diameter; however, after observing simple linear cuts under a microscope this speed was consider to be high, so an initial override of 50% was done directly in the machine controller.

Since the selected machine has 5 axes available, it is possible to use those axes in order to compensate for the taper angle that is created due to the dynamic nature of the waterjet. To properly use the taper compensation, it is necessary to calibrate the machine depending on the material and thickness. This calibration can be done by cutting a square of a known size, 10 mm in this case, and measure the deviation, both in the top geometry and in the bottom surface.

The compensation in the top geometry is done directly into the machine settings under the “radius compensation” option. The compensation works as follow: Once the deviation from the design is measured, the difference is input in the radius compensation field adding the value if the cut geometry is smaller or subtracting if the geometry is bigger.

The compensation for the bottom geometry involves the use of IGEMS since the taper angle compensation is directly calculated by the software, Figure 17. The difference measured in the cut piece is input into the material settings field, both top and bottom, so the software is able to calculate the compensation angle to achieve a straight cut.

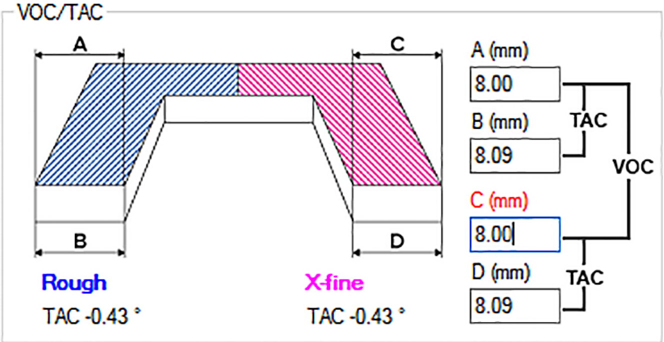


Figure 17. Tapper angle compensation in IGEMS

The final selected values for feed rate, radius compensation and taper angle compensation are provided in Table 6.

Table 6. Radius compensation, feed rate and taper angle compensation

Nozzle diameter	Radius compensation	Feed rate	Tapper angle compensation
[mm]	[mm]	[mm/min]	[°]
0.5	0.235	26	-0.43°
0.4	0.168	15	-0.43°
0.3	0.190	10	-0.43°
0.2	0.130	8	0.14°

The abrasive waterjet is a dynamic tool, hence some additional phenomena are observed and described below. In order to simplify but also create an understanding of the main issues and phenomena, apart from the literature mentioned issues, the following were chosen to be further explained:

- **Orifice cracks:** During operation of the machine under standard configuration, the water flow and the abrasive flow are stopped at the same time. However, when the needle valve that stops the water flow is closed, a high pressure difference is created. This pressure difference can result in the drag back of the abrasive waterjet into the jewel orifice, producing a crack in the same.

- **Clogging:** Clogging of the nozzle can occur for several reasons. One reason is that the current machine configuration has an intake of air into the abrasive container that takes the air from the inside of the machine, which results in humidity in the abrasive, preventing the abrasive grains to flow individually. One more factor that leads to clogging is the grit size of the abrasive; the recommended grit size, according to literature, is the one that provide grains of one third in size compared to the nozzle diameter in use. Furthermore, the alignment of orifice and nozzle is done by mechanical means, and if the components involved are tightened with excess it may result in a misalignment that leads to water splashing in the intake of abrasive, preventing the flow of abrasive and ultimately clogging the nozzle.

- **Deformed cut even at low feed rates:** Since the waterjet is a dynamic tool, as the cutting head moves forward, the jet has a lag in the tail, which is eroding the material in the bottom surface of the material, resulting in a difference in geometry between top and bottom surface.

3.1.2 Process planning

With the cutting parameters properly selected, the next step is the creation of the tool path. Since the design is a spur gear, it is possible to use a 2D drawing extracted from the CAD file. Once the drawing is imported into IGEMS, a solid model is created which will contain information related to the component that is going to be machined, such as type of material, thickness, tapper compensation, etc.

One relevant feature that is available when the solid part is create is the “geometry optimization” function. This function will analyse if the selected will be capable to fit into all the geometric features describing the part. In case there are part features which are too small for the waterjet to go through, the part will be created with a stock of material in those sections where the jet does not fit. These option can be seen in Figure 18.

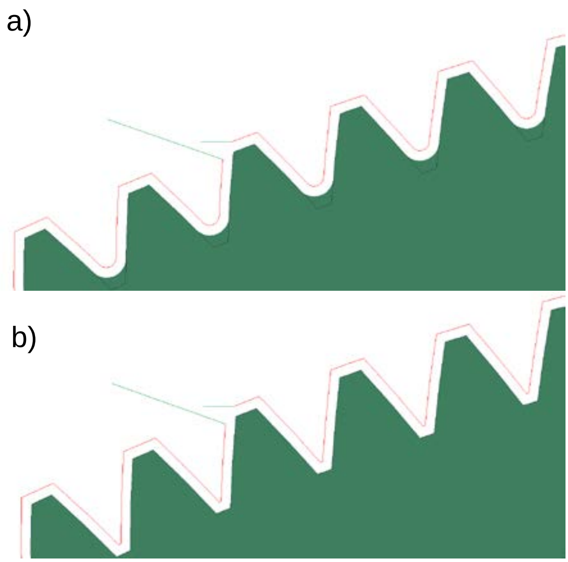


Figure 18. a) Part with geometry optimization, b) Part without geometry optimization

In addition, among the parameters to be selected when a part is created, the desired quality is to be selected. The quality in IGEMS is related to the feed rate that will be used in the machining process. The available qualities are: X-rough, rough, medium, fine and X-fine; where X-rough has the highest feed rate and X-fine is the opposite with the lowest feed rate. However, if, after experimentation and sufficient practice, the user notice that the values set in the software are not optimum, it is possible to alter them to fit the application in hand. Furthermore, is it is desire to have different cut qualities within the same part, it is possible to select specific areas of the part to have specific quality.

Once the solid part is created, it is possible to create the tool path for the machine. The most relevant options to select for the tool path are three: 1) piercing, 2) lead in, and 3) lead out. There are a group of piercing depending on the motion that the cutting head will do, for instance circular or linear; for the experiments a circular piercing was selected. Both lead in and lead out can be modified in terms of length, angle and overcut, which will result in small marks in the material in the entry and exit points depending on the hardness of the material and selected values. For the experiments a linear lead in and lead is selected, with angles of 80° and 20°, respectively, with no overcut.

The final step in the processes planning is the post processing of the tool path to obtain a NC code that will be the input for the waterjet machine; in addition, when the NC code is created, the software generates the workpiece origin automatically, or a specific point can be selected if the need is present.

3.1.3 Experimental setup

With the NC code generated by the CAM software, the next step is to set the material in the machine, set the desire parameters and load the NC file.

For this experiments, the Armox 500T plate was placed on top two parallel bars that suspend the material over a water tank inside the machine. With the plate positioned in the selected location and the NC code loaded in the machine, it is necessary to set a zero position for the nozzle, that will be correlated to the origin of the workpiece in the NC code. This process is done manually.

The machining of the gears was done with the material plate submerged under water. The main reason behind is to reduce noise level during the cutting processes of the pieces.

3.2 Metrology

In order to determine which of the combinations of jewel orifice-nozzle is the one that provides the best results, measurements were made for profile and index deviations. After selection of the most suitable pair orifice-nozzle and a complete gear is manufactured and measure to determine the highest quality that can be achieved with the actual configuration.

The equipment that was used for measurement purposes is:

- Profile and index deviation: Nikon Optiphot 150, 5X magnification microscope with DeltaPix InSight software, Invenio-8DII CCD camera, NIKON TV LENS C-0.45X
- Runout: CMM Crysta Apex S7106, Mitutoyo Gearpak
- Surface roughness: Zygo NewView 7300 optical 3D profilometer
- Hardness: HR-521 (L) /523 (L) Series 810-Rockwell Type Hardness

The measurements obtained from the Gearpak are compared to a gear manufactured by conventional processes, hobbing → hardening → grinding.

In order to measure the profile and index deviations, the following measuring technique was adopted: the design geometry of the gear is exported using Autodesk Inventor at the same scale as the images exported by DeltaPix InSight software. The microscope captured images are then overlapped with the design geometry. Next, linear measurements are taken between the geometric profile of the captured image and the design.

For the surface roughness, a square with edge length of 1.09 mm is used to study the roughness average value in a white light interferometer. The measurements are performed in a flank and following cutting feed direction.

3.2.1 Profile and Index deviations

In order to measure the profile and index deviations, the following measuring technique was adopted: the design geometry of the gear is exported using Autodesk Inventor at the same scale as the images exported by DeltaPix InSight software. The microscope captured images are then overlapped with the design geometry. On the obtained images, linear measurements are taken between the geometric profile of the captured image and the design.

This method is useful to measure the maximum deviations in profile, and can be used as a rule of thumb to approximate the quality of a gear. In addition, measurements for the final gear are performed using the CMM Crysta and Gearpak software module in order to determine the quality of the gear according to DIN3967. For profile and index deviations the measurements are taken on 4 teeth of the outer diameter in both AWJ machined and conventional machined gears.

3.2.2 Runout

The runout is measured using CMM Crysta Apex S7106 machine.

In order to measure the runout of the manufactured gear, a scan of the final gear is made using the CMM. The radial runout was measured on every tooth in the outer profile. The inner profile was not measured since the probe was not able to fit into the diameter.

3.2.3 Surface roughness

Surface roughness is measured using Zygo NewView 7300 optical 3D profilometer.

For the surface roughness, a square with edge length of 1.09 mm is used to study the roughness average value in a white light interferometer. The measurements are performed in a flank and following cutting feed direction.

3.2.4 Hardness

Material hardness measurements are taken using HR-521 (L) /523 (L) Series 810-Rockwell Type Hardness testing machine.

The measurements for the hardness in the gear manufactured with AWJM have been taken in three different points of the top surface. For the machined gear by traditional methods, the measurements have been performed in the top surface of the most prominent edge; it is important to mention that the equipment used for this test is designed to measure hardness in Rockwell C scale, values that were converted to Brinell scale HBW in order to compare the hardness of the AWJ manufactured wear to the information provided by the supplier.

4 Results

The following chapter presents the principal results obtained from the experiments performed during this project. Results include measured deviations in profile and index deviations, runout, surface roughness and hardness. The most representative results are presented in order to provide a clear picture, while the rest of results is present in Appendix A.

4.1 Profile deviation results

The first run of experiments consisted in the machining of ten teeth of the outer diameter of the gear to test the capability of each pair of orifice-nozzle available (described in section 3.1.1). After examination of the dimension of the gear, it was noticed that the smallest dimension is the size in the root circle between two teeth, with a value of 0.35 mm in the design. Therefore, the 0.4 mm and 0.5 mm nozzle were discarded since it is not possible to machine the complete profile of each tooth up to the root.

After performing the machining, the best results are obtained with the pairs 0.10:0.3 mm orifice -nozzle, and 0.17:0.3 mm orifice-nozzle. The result for 0.17:0.3 mm pair can be seen in Figure 19 (right).

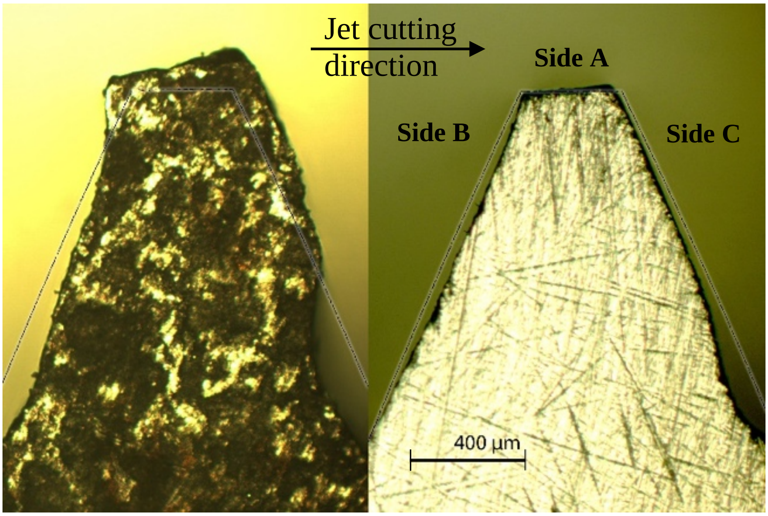


Figure 19. Bottom surface profile deviation illustration. Comparison between the 0.2 mm (left) and 0.3 mm (right) nozzle cut

A graphical description of the bottom geometry deviations comparison between the initial maximum geometric accuracy values measured on side A, side B and side C, Figure 19, of the 0.2 mm and 0.3 mm nozzle diameter can be seen in Figure 20. An improvement of 83% was obtained in the maximum deviation measured in the top part of the teeth at the bottom surface, while in the left and right flank the improvement is 48% and 66%, respectively.

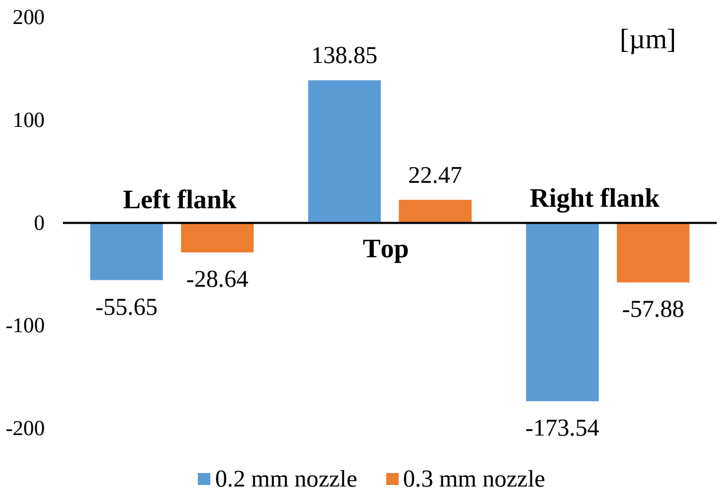


Figure 20. Maximum bottom surface profile deviation comparison between 0.2 mm and 0.3 mm diameter nozzle

The top geometry deviations measured on the same Side A, B and C for a 0.3 mm cut, display a maximum value of 7 µm with an average value of 4 µm.

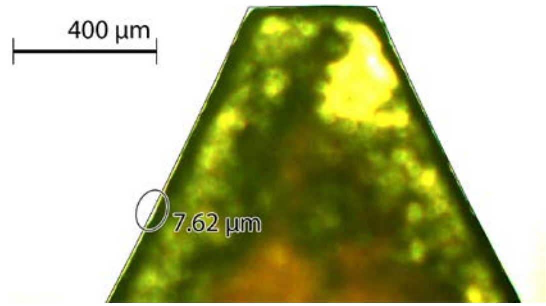


Figure 21. Top geometry, inner tooth, gear A

Side A of the bottom geometry of both dear A and B presented an extra material in the second corner (marked in red in Figure 22), which could be later corrected up to some extent for gear A, and completely for gear B by reducing the feed rate.

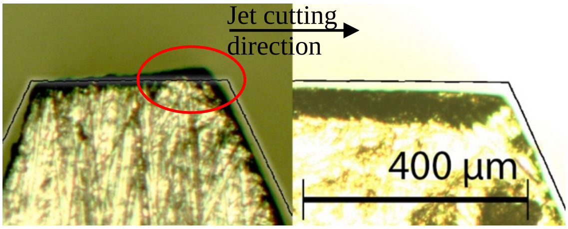


Figure 22. Bottom geometry Side A material removal. Gear A (left image) and gear B

Side C of gear B, presented an undercut in the root radius section. This error in the geometry is assumed to be result of a high feed rate and low control of the motion in the cutting head. Figure 22 shows how the undercut can be corrected by decreasing the feed rate of the process; process that at the moment has to be done manually after experimentation.

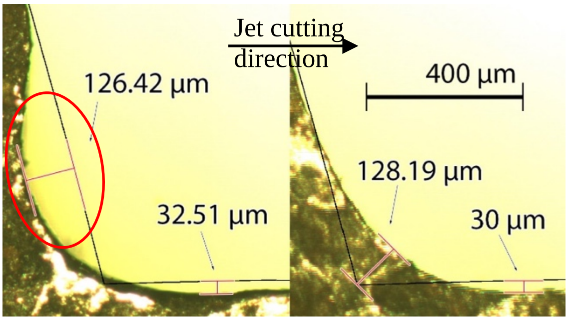


Figure 23. Bottom geometry Side C undercut of gear B; feed rate 36 mm/min (left image) and 11 mm/min

Figure 23 presents the undercut generated in the bottom geometry of gear A, in the same manner as in gear B. However, it can be appreciated that both sides B and C present undercut, nevertheless with different behaviour on each side.

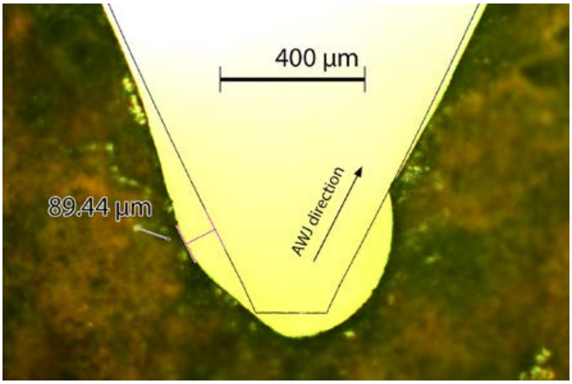


Figure 24. Bottom geometry, inner tooth, gear A

In addition, it was observed with every cut performed during the experimentation phase of this thesis project, that the top surface of the material presents a round corner. This round corner can be appreciated in Figure 25; however, it is important to mention that the length (seen as 374.38 in Figure 25) of the roundness decreases as the cutting power increases.

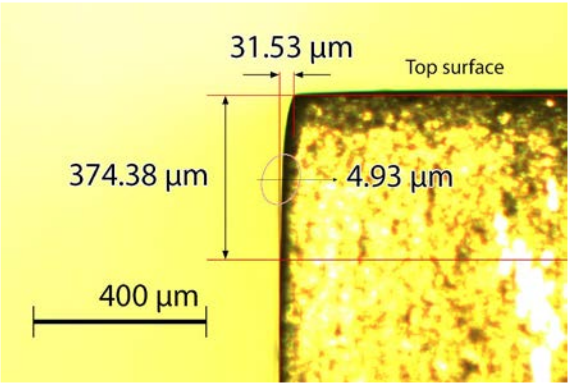


Figure 25. Round corner effect of a straight cut. Section view

4.1.1 AWJM gear compared to conventional machined gear

A comparison has been made between a gear manufactured by conventional machining processes and one manufactured by AWJ machining. The results presented here are measured using a CMM and then analysed with Mitutoyo Gearpak module of MCOSMOS software.

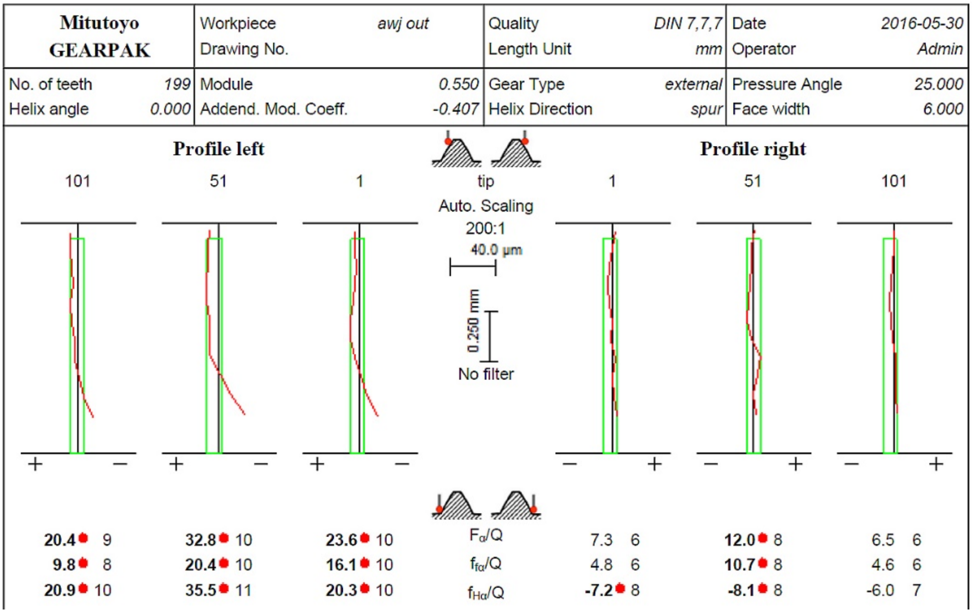


Figure 26. Profile results of AWJM outer gear

The green box in Figure 26 represents the tolerance limits stablished in the DIN3967 standard according to Q7. The gear manufactured using AWJM achieved values of Q10, Q10 and Q11 for F_α (Total profile error), $f_{f\alpha}$ (Profile form error) and $f_{H\alpha}$ (Profile angle error), respectively. From Figure 27 it can be appreciated that the AWJM gear left profile is out of tolerance for Quality 7, however the average quality value of the right profile for F_α, $f_{f\alpha}$ and $f_{H\alpha}$ are within Q7 tolerances. This difference between left and right flank are correlated to the variation in profile observed in Figure 19, section 4.1.

Profile left

		F_α		$f_{f\alpha}$		$f_{H\alpha}$	
Max. value	Q	32.8	10	20.4	10	35.5	11
Avg. value	Q	25.2	10	15.9	9	23.3	11

Profile right

		F_α		$f_{f\alpha}$		$f_{H\alpha}$	
Max. value	Q	12.0	8	10.7	8	-8.1	8
Avg. value	Q	8.8	7	7.7	7	-6.1	7

Figure 27. Maximum and average quality of left and right profile of AWJM outer gear

In comparison, the results for the gear produced with conventional hobbing and grinding technologies also presents results out of tolerance for Q7, Figure 28. In Figure 29 can be seen that Fα, $f_f\alpha$ and $f_H\alpha$ are out of Q7 tolerances, reaching values higher than Q12 tolerances.

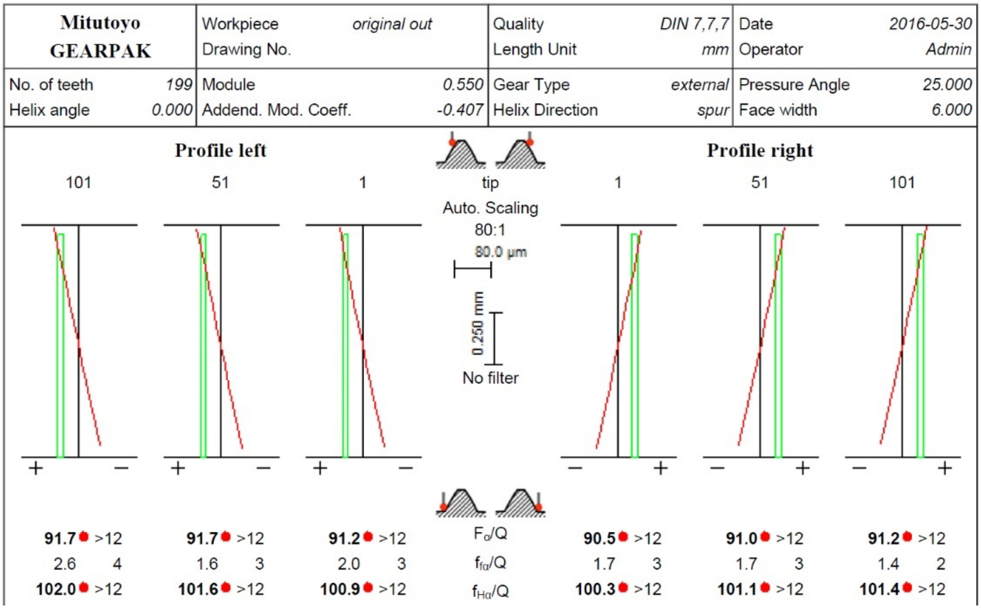


Figure 28. Profile results of conventional machined outer gear

Profile left

		F_α		$f_{f\alpha}$		$f_{H\alpha}$	
Max. value	Q	**91.7**	>12	2.6	4	**102.0**	>12
Avg. value	Q	**91.3**	>12	1.8	3	**101.3**	>12

Profile right

		F_α		$f_{f\alpha}$		$f_{H\alpha}$	
Max. value	Q	**91.2**	>12	2.2	4	**101.4**	>12
Avg. value	Q	**90.9**	>12	1.8	3	**100.7**	>12

Figure 29. Maximum and average quality of left and right profile of conventional machined outer gear

Regarding the flank line, the AWJM gear obtained and average of Q10 for F_β (Flank line trace error) in both flanks, Q7 for $f_{f\beta}$ (Flank line form error) in both flanks and Q1 and Q2 for $f_{H\beta}$ (Flank line angle error) for left and right flank respectively. On the other hand, the gear manufactured by conventional manufacturing processes presents tolerances that comply to Q1 and Q2 for flank line trace error, Q4 and Q2 for flank line error form and Q1 for flank line error form.

Flank line left

		F_β		$f_{f\beta}$		$f_{H\beta}$	
Max. value	Q	**41.9**	10	**9.7**	9	**-46.4**	11
Avg. value	Q	**28.8**	10	6.5	7	0.9	1

Flank line right

		F_β		$f_{f\beta}$		$f_{H\beta}$	
Max. value	Q	**50.3**	11	**8.2**	8	**-49.6**	11
Avg. value	Q	**30.9**	10	6.6	7	-2.0	2

Figure 30. Flank line quality for AWJM outer gear

Flank line left

		F_β		$f_{f\beta}$		$f_{H\beta}$	
Max. value	Q	3.0	2	3.1	4	-1.6	1
Avg. value	Q	2.7	2	2.2	2	-0.9	1

Flank line right

		F_β		$f_{f\beta}$		$f_{H\beta}$	
Max. value	Q	1.9	1	1.8	2	1.3	1
Avg. value	Q	1.7	1	1.6	2	0.9	1

Figure 31. Flank line quality for conventional machined outer gear

4.2 Runout

The runout results are obtained in the same manner and with the same equipment as the profile deviation ones.

The results obtained shown a total radial runout (F_r) of the AWJM gear of 97.1 µm, which indicates a quality level 12, with maximum and minimum values of 41 µm and -56 µm, respectively. Figure 32 shows the distribution of the runout throughout the teeth.

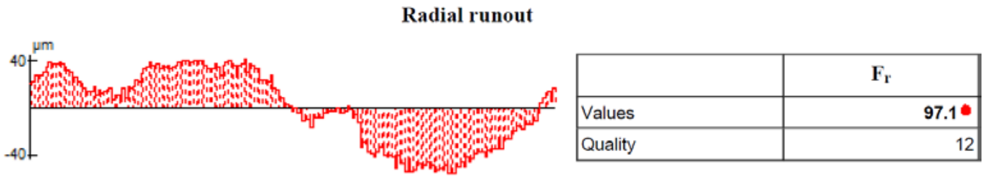


Figure 32. Radial runout of AWJM outer gear

On the other hand, the gear machined with conventional methods presents a total radial runout of 45.5 µm, complying with quality level 10, Figure 33, with maximum and minimum values of 21 µm and -24 µm, respectively.

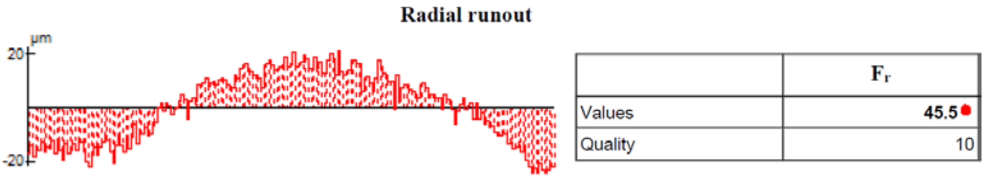


Figure 33. Radial runout of conventional machined outer gear

4.3 Surface roughness

The results on the surface roughness displayed Ra values ranging from 0.8 µm to 1.9 µm. The black line in Figure 34 shows the direction of measurement for the Ra 1.41 µm, perpendicular to the cutting direction. The red tops observed in the right side of Figure 34 explain the systematic waviness of the machined surface, result of the dynamic variation in the abrasive waterjet due to lag and variation in pressure.

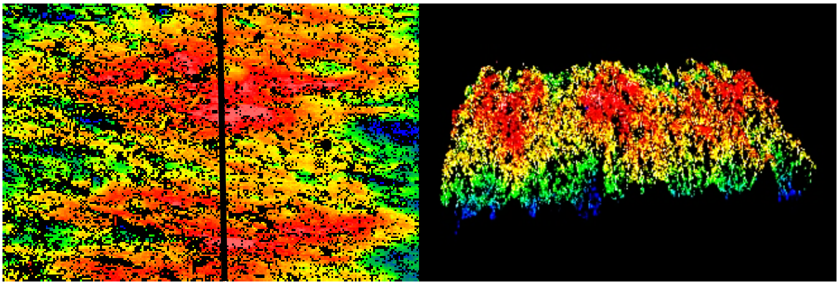


Figure 34. AWJM gear bottom, left tooth flank, 36 mm/min cut; Ra 1.41 µm

It is relevant mentioned that surface roughness is largely affected by abrasive grit size. If surface roughness quality is to be improved, finer abrasive should be used [24].

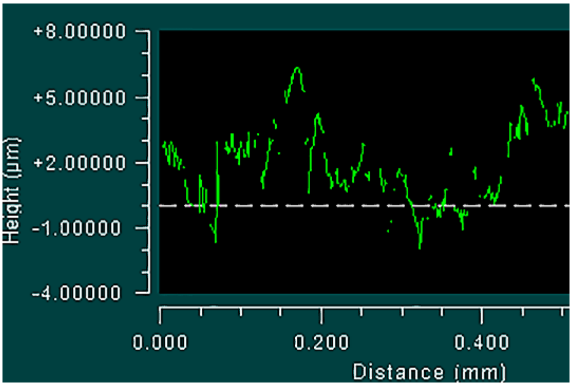


Figure 35. AWJM gear, left tooth flank

Due to the impossibility to access the flanks of the conventional machined gear, a comparison could not be made.

4.4 Hardness

The hardness test provided the following results:

Table 7. Hardness test results

[HBW]	AWJM gear	Conventional machined gear
Hardness	~ 481	~ 258

5 Discussion and conclusions

In this chapter conclusion is presented based on the results previously presented. In addition, a discussion and explanation for the results is provided.

5.1 Answers to research questions

- **Q1:** Is it possible to produce precision gears using abrasive waterjet machining, and if so up to what point?

The current high precision AWJM may operate with the chosen material resulting in geometry deviations of 20-40 microns for the studied quality features. Measurements show that it is possible to produce a gear within DIN3967 level Q10 in average. In comparison, the gear manufactured by hobbing and grinding showed a Q12 level; however, after analysing Figure 20 it is safe to speculate that this result may be due to an error in the manufacturing process, specifically the grinding wheel that was used to produce it. This conclusion is based on the fact that the measurements from Gearpak presents a line with a slope throughout the flank profile with low deviations.

In addition, it is relevant to mention that tolerances specified in standards increase as the gear module increases, so AWJM presents better results for working in larger tolerance ranges.

- **Q2:** What kind of hybrid technology can be implemented to enhance abrasive waterjet machining to produce precision gears?

On the hybrid part, we have found that the suitable and feasible finishing techniques will be grinding for the outer gear and broaching or power skiving for the inner gear. This however, may present future problems in defining the datum surfaces to be used for further processing.

Further investigation and testing is needed in order to safety determine whether these suggestions are feasible or not.

- **Q3:** What are the potential benefits if the industry changes the current method to manufacture gears, to a more flexible and environmental friendly method?

As stated during section 2.2, AWJM has several advantages over conventional machining methods. Important enfaces should be made into the friendliness of AWJM to the environment, since no toxic residues are produce like the lubricants that are necessary to manufacture with hobbing for instance.

In addition, the flexibility in terms of tooling that AWJM provides to the industry are of high importance since it reduces lead time and cost by eliminating the tooling design and manufacturing. Also, flexibility to redesign a part is significantly increase if AWJM is adopted as production method; this redesign can help to improve the quality of a gear regarding failure as result of fatigue in the tooth root by changing the geometry as investigated by Brecher *et al.* [5].

During operation of the machine, it present low setup times and is a relative easy to learn software and machine.

5.2 Discussion and conclusions

The results revealed that the AWJ machine together with the CAM software and machine controller presents high potential of producing ISO quality standard gears. By comparing the results between the gear A and gear B, it is concluded that each particular geometry design needs to have its own specific process parameters. In order to achieve a correct cut in the bottom geometry, sufficient cutting power is needed; this means that there is a limitation on the smallest nozzle diameter and orifice that can be used for a specific material thickness and hardness. The top geometry deviations are influenced by the standoff distance of the nozzle. If the pivoting point of the water jet is not found on the same plane with the top geometry of the cut part, the taper angle compensation for the bottom geometry will affect the top geometry. Top surface section presents a systematic rounded corner, effect which diminishes with the increase of cutting power, Figure 25 section 4.1. The surface roughness values obtained in this study are satisfactory for ISO standards. The IGEMS software algorithms were designed and optimized for larger geometries than studied in this work, information which points that further experimentation is needed, after corrections are made, to allow working with smaller designs. The IGEMS software and controller use a look ahead function and interpolator that is believed to help in particular cases for better control of the water jet, improve the cut quality or eliminate jet lag negative effects. A more in depth understanding of the machining system will help chose the correct cutting parameters for a specific part. If appropriate fixtures are used for a given part, no deburring process is needed; however, working with composite materials, delamination is common due to the impact of abrasive grains. This outcome can be avoided using SUPER-WATER® [28]. Operation with nozzles with diameters as low as 0.1 mm is possible and can help achieve lower radius corners on the inside geometry of a cut part. However, the quality of the cut and suitability to use lower diameter nozzles are subject for further investigation.

Tungsten nozzles present deviations from the desired circular nozzle design. According to the equipment manufacturer, the manufacturing process of the tungsten nozzles presents difficulties in achieving the correct stated dimensions; i.e. a 0.3 mm diameter nozzle will present in practice deviations of 10-15% of the nominal diameter value.

When referring to orifice wear, water quality is also an influencing factor. More impurities present in the water will lead to a higher wear rate and degradation of the orifice geometry.

5.3 Further improvements and future work

The results presented in this thesis are limited to the utilized and studied equipment. A rough optimisation of cutting parameters has been made together with software and equipment manufacturer. Further work for optimisation would have extended beyond the allocated time for the thesis.

Investigations for future work include:

- Investigation of the effect of a curvature in the edge of the top initial damage region of every cut. This effect has been observed to reduce as the size of nozzle diameter increases (Figure 21, section 4.1).

- Correction of the top and bottom surface geometry difference by working with a 3D model that compensate the bottom surface geometry.

- The dynamic nature of AWJM makes it highly dependent on the environment in terms of water quality, ratios between orifice and nozzle, abrasive type and grit size, moisture in the environment, etc. Further improvement could be achieved if control systems are developed to control the previous mentioned variables.

- A systematic variation of ~10-20 µm was found on simple geometries during the calibration processes. This deviation can be related to inaccuracies in the mechanical components of the machine and are reflected in the final workpiece. If this is to be true, a compensation method could be developed to eliminate the variations.

- Investigation of higher control of waterjet by creating a 3D model in IGEMS and providing a smoother control and “bottom first” approach to specific section of the geometry in order to reduce the effects of jet lag, in combination with different quality sections in the gear, to reduce the systematic different in geometry between the top and bottom surface.

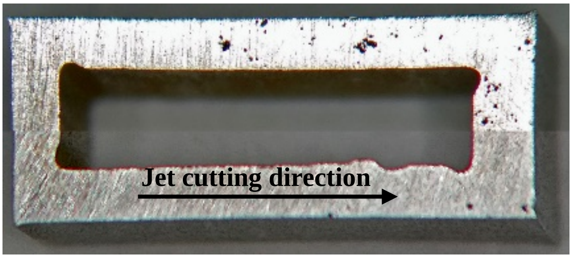


Figure 36. Simplified illustration of systematic jet lag effects on an inside square cut

- Finding new materials for focusing nozzles that have a higher wear resistance capability.

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Appendix:

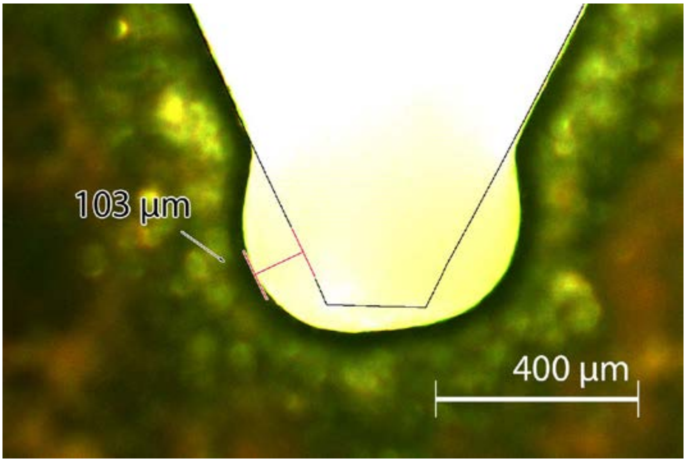

Figure A. Top geometry, inner teeth, gear A

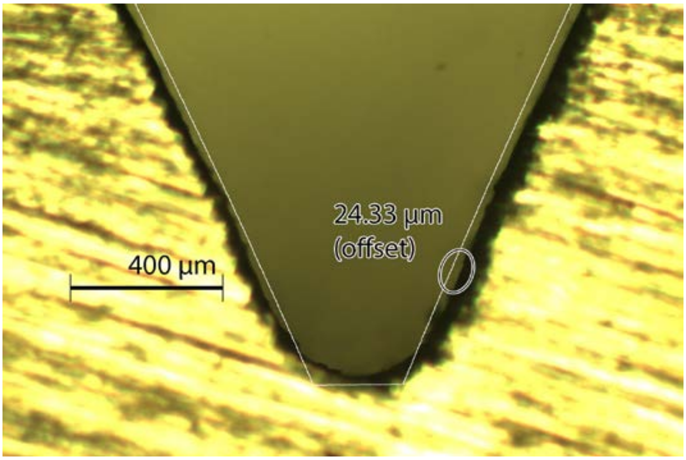

Figure B. Top geometry, outer teeth, no TAC, gear A

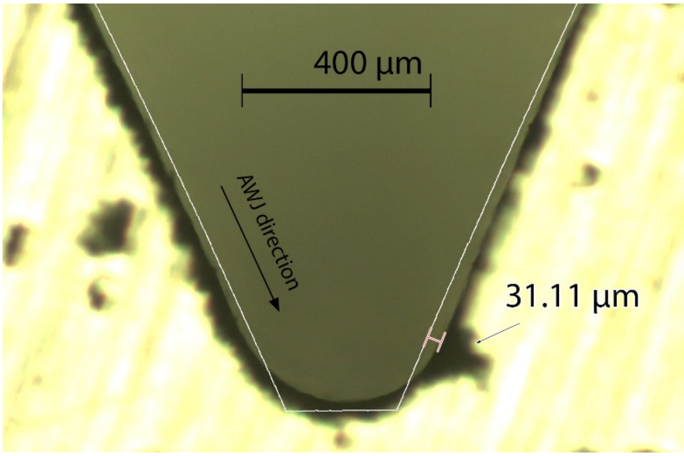

Figure C. Top geometry, outer teeth, gear A

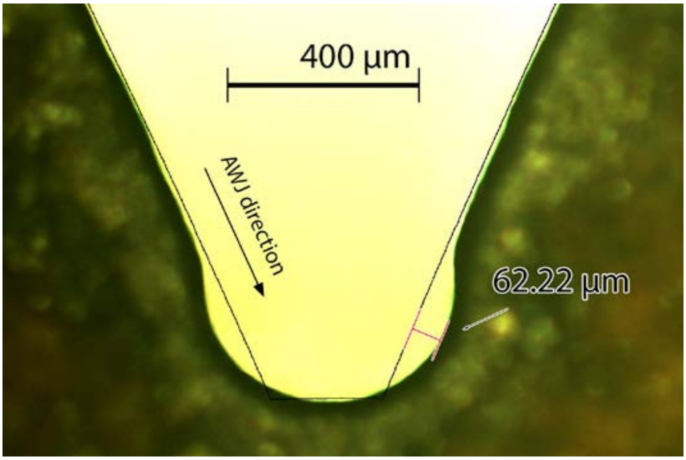

Figure D. Top geometry, outer teeth, gear A

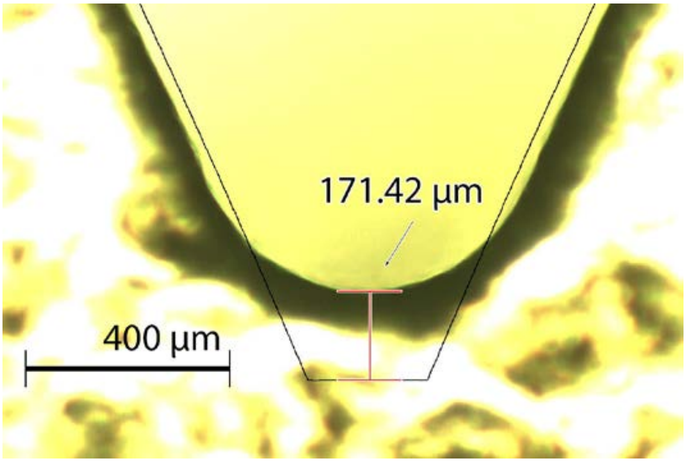

Figure E. Top geometry, outer teeth, geometry optimisation, gear A

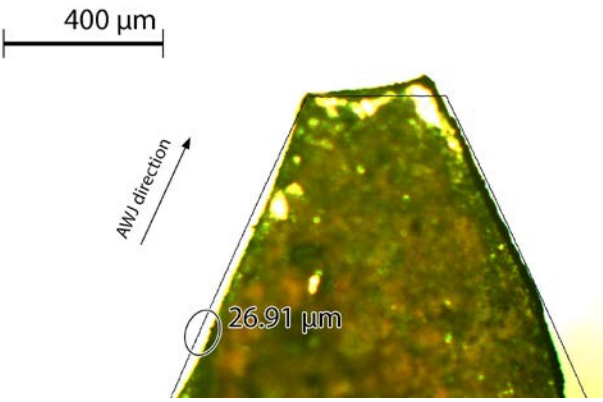

Figure F. Bottom geometry, outer teeth, gear A

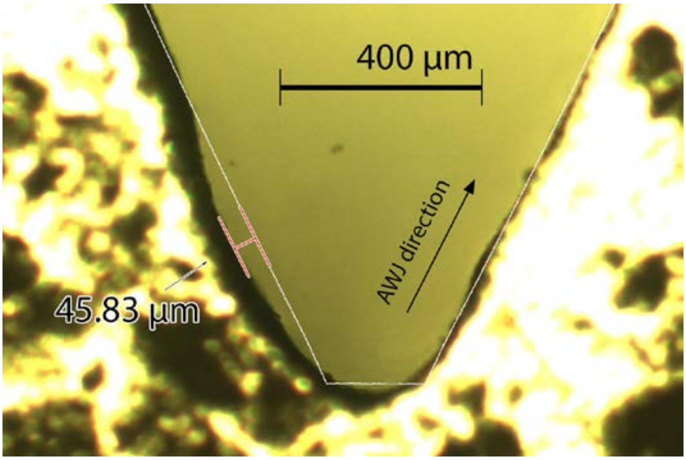

Figure G. Bottom geometry, inner teeth, no TAC, gear A

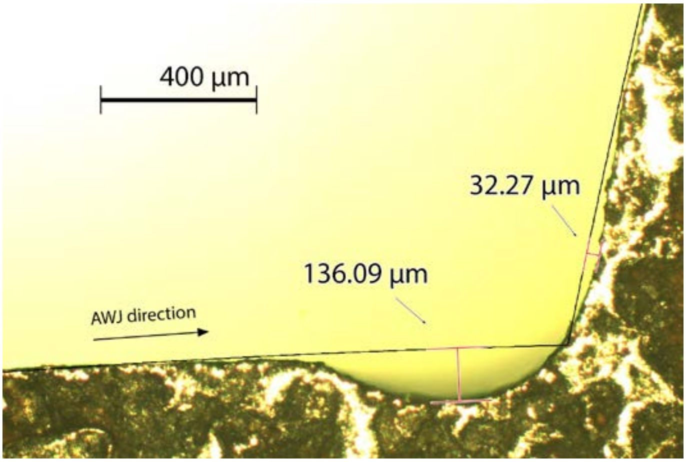

Figure H. Bottom geometry, feed rate 36 mm/s, undercut right side, gear B

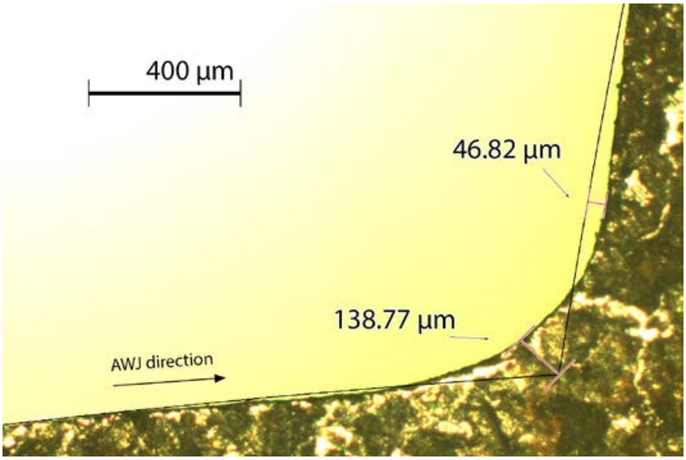

Figure I. Bottom geometry, feed rate 11 mm/s, undercut right side, gear B

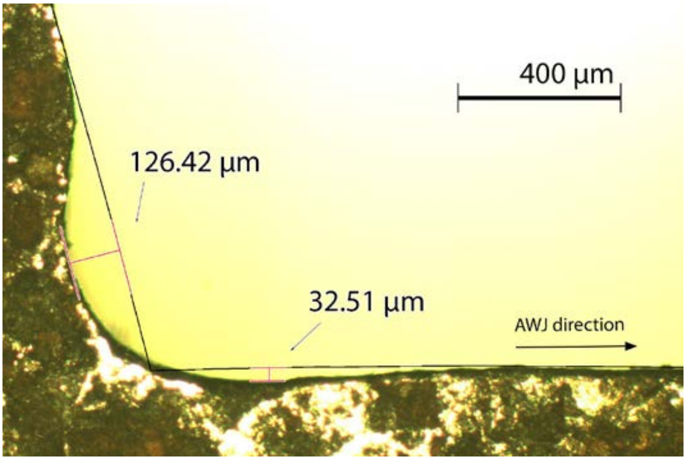

Figure J. Bottom geometry, feed rate 36 mm/s, undercut left side, gear B

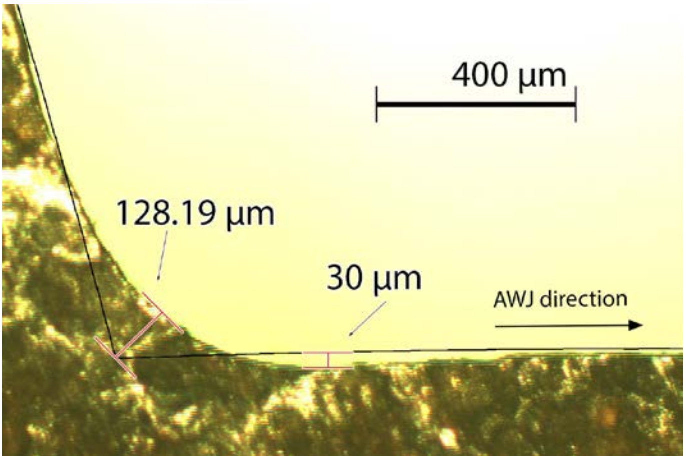

Figure K. Bottom geometry, feed rate 11 mm/s, undercut left side, gear B

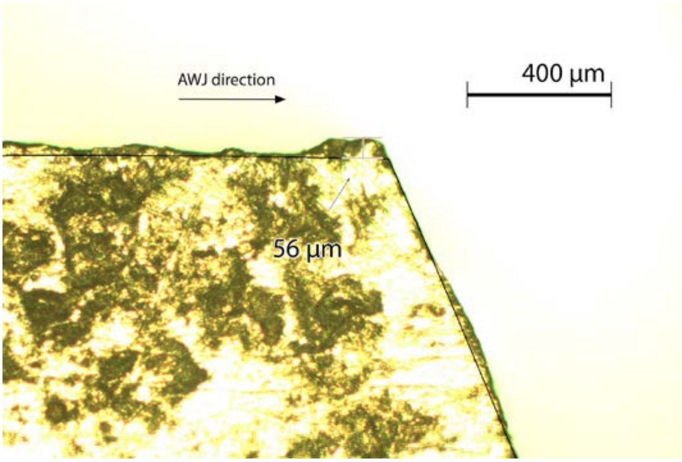

Figure L. Bottom geometry, feed rate 36 mm/s, tooth right side, gear B

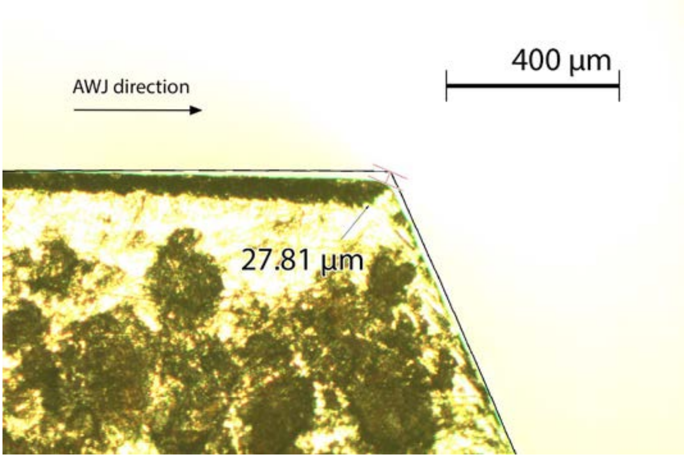

Figure M. Bottom geometry, feed rate 11 mm/s, tooth right side, gear B

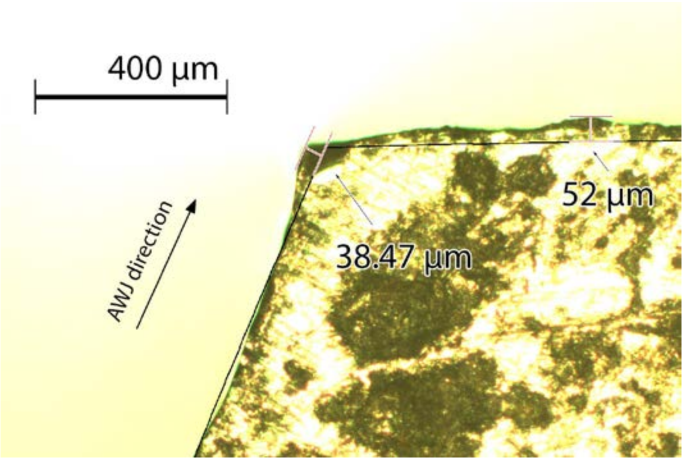

Figure N. Bottom geometry, feed rate 36 mm/s, tooth left side, gear B

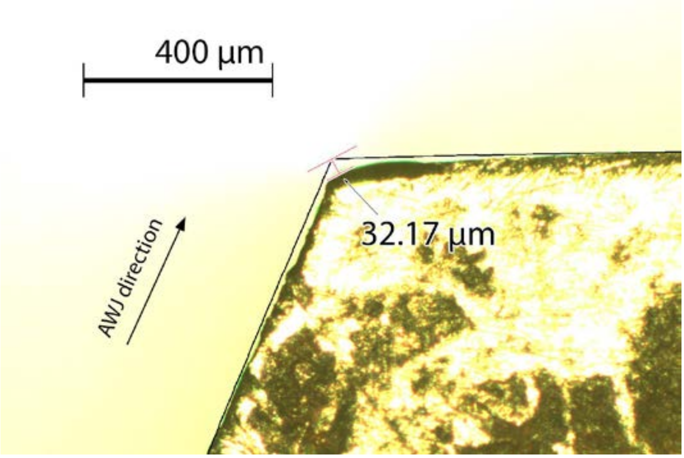

Figure O. Bottom geometry, feed rate 11 mm/s, tooth left side, gear B