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Additive manufacturing for field repair and maintenance of the assault rifle AK5C – a feasibility study

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Abstract

Additive manufacturing for field repair and maintenance of the assault rifle AK5C – a feasibility study

Emmelie Simic

The main purpose of this thesis is to see if it is possible to use additive manufacturing (AM) for field repair and maintenance of the assault rifle AK5C, by finding a suitable additive manufacturing process and make a functional evaluation of the additive manufactured components: hammer axis, gas cylinder and the magazine follower. The Swedish Defense Materiel Administration (FMV) is an administration that supplies the Swedish armed forces with materiel. Therefore, it is in their interest to investigate if it is possible to use AM for field repair and maintenance in example Mali or Afghanistan.

Based on a survey, and the fact that the components are purely structural Powder Bed Fusion AM was selected. The hammer axis was made in a margining steel MS1, the gas cylinder in the nickel-alloy called Inconel 718 and the magazine follower was made in a polymer called nylon 12.

The functional evaluation of the components took place at Saab in Östersund, where each component was placed in the rifle. The rifle was fired 1000 rounds with the hammer axis, 1000 rounds with the gas cylinder and 500 rounds with the magazine follower. The functional test for the components was successful, there were also no major changes in dimensions and weight except for the hammer axis. The diameter for the hammer axis went from 5,00 mm before the functional test to 4,98 mm after the functional test. The microscope images showed that abrasion had occurred, not only for the hammer axis but also for the magazine follower, due to friction. Firing speed was also measured and it should be over 600 rounds/min, if everything works properly. The hammer axis had a firing speed of 639 rounds/min which is good while the gas cylinder only had a firing speed of 595 rounds/min. This was because the inner diameter of the cylinder was too big, causing gas leaking and pressure drop inside the gas cylinder.

In conclusion, additive manufacturing does allow for fabrication of functional spare parts – at least these evaluated here.

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Additiv tillverkning för fältreperation och underhåll av eldhandvapnet AK5C – en genomförbarhetsstudie

Emmelie Simic

Additiv tillverkning även känd som 3D-printning, är en tillverkningsmetod där en komponent oftast byggs med en lager-på-lager-teknik. Den kännetecknas av att man adderar material, med t.ex. pulver eller tråd, istället för att ta bort material från ett arbetsstycke som är tillverkat med exempelvis gjutning eller formsprutning. Produktionen av delar som man vill tillverka sker i ett digitalt kontrollerat steg där man inte behöver använda sig av några konventionella verktyg eller formar. AM, från engelskans *Additive Manufacturing*, har blivit en betydelsefull framställningsmetod de senaste åren och förväntas revolutionera tillverkningsindustrin. Fördelarna med AM är att man lätt kan byta design på den komponent som man vill framställa samt att väldigt komplexa geometrier tillåts. AM har primärt använts for prototypframtagning, men har på senare tid även använts för att framställa kommersiella produkter inom t.ex. flyg- och medicinindustrin.

Försvarets materielverk, FMV, är en myndighet som förser det svenska försvaret med materiel så som flygplan, vapen, utrustning för soldaten samt vagnar och stridsfordon. Därför är det intressant för FMV att se om det är möjligt att använda sig av additiv tillverkning för att kunna framställa reservdelar i fält i t.ex. Mali eller Afghanistan. Även om AM är något som har utvecklats inom den civila sektorn, tror European Defence Agency att AM har stor potential att förbättra försvarsförmågan. Med det menas t.ex. rörlighet, hållbarhet, kraft och skydd, fältreparation och fältunderhåll samt möjlighet till minskad logistik börda.

Huvudsyftet med det här examensarbetet var att se om det är möjligt att använda sig av additiv tillverkning för fältreperation och underhåll av eldhandvapnet AK5C. Tre komponenter valdes, två i metall och en i plast: hanaxeln, gascylindern samt patronföraren. Materialen de var framställda av samt vilka påfrestningar de får utstå under skjutning undersöktes för att kunna ta ett beslut om vilken additiv tillverkningsmetod som skulle användas samt vilka material de skulle bli framställda i. Inom additiv tillverkning finns det nämligen sju olika processkategorier med underkategorier, beroende på vilken metod som används vid framställning, materialet samt teknologin för maskinen. Den mest lovande metoden för de tre komponenterna var Powder Bed Fusion (PBF), vilket är en pulvermetod där antingen en laser eller elektronstråle används för att smälta och foga samman pulver/material för varje lager som byggs. Selective Laser Sintering (SLS) och Direct Laser Metal Sinering (DLMS) är två tekniker som finns inom metoden PBF och det är de som användes vid framställning av de tre komponenterna. SLS framställer i plast och DLMS i metall. Patronföraren är framställd i materialet nylon 12 med SLS, medan hanaxeln och gascylindern är framställd med DLMS i verktygsstålet MS1 respektive nickellegeringen Inconel 718.

Efter att komponenterna hade framställts, genomfördes ett funktionstest på Saab i Östersund. Komponenterna placerades i vapnet och hanaxeln samt gascylindern klarade en funktionsskjutning av 1000 skott och patronföraren 500 skott utan att gå sönder.

Förutom det funktionella testet, mättes och vägdes komponenterna både före och efter skjutning vilket inte visade på några större förändringar förutom för hanaxeln. Före skjutning hade

hanaxeln en diameter på 5,00 mm och efteråt hade den en diameter på 4,98 mm. Mikroskopering visade nötning på både hanaxeln och patronföraren.

Eldhastigheten för vapnet ska normalt vara minst 600 skott/min. Hanaxeln medgav en eldhastighet på 639 skott/min medan gascylinder medgav en eldhastighet på 595 skott/min. Det senare, lägre värdet berodde på att innerdiametern på gascylindern var för stor så att gas läckte ut på sidorna och medförde att trycket sjönk i gascylindern.

Additiv tillverkning ser sammanfattningsvis ut att vara ett fungerande sätt att framställa reservdelar av olika slag, åtminstone de som har testats och utvärderats här.

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Foreword

This master thesis was performed at The Swedish Defense Materiel Administration (FMV) during autumn 2017 and is a part of the master's degree of materials engineering at Uppsala University.

First of all I would like to thank my supervisor Joakim Lewin for all of the support and believing in me throughout this process. I am very grateful for this opportunity that you gave me and for letting me work independently.

I would also like to thank everyone at SPL armé who took great care of me and treated me as one of your own. Not to mention, thank you Jonas Persson for all your expertise and for joining me on the field trip to Spain it was truly an experience. Thank you Vickan for sharing office with me and for all the conversation we had. I am also very grateful to Per Cederberg for answering all the technical questions that I had, made me think outside the box and go out of my comfort zone.

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Last but not least I am very grateful to my supervisor Greger Thornell for making me struggle with this thesis and for being the person that helped me when I got stuck through this process. I know I have been stubborn but I want you to know that I am very grateful that you are even more stubborn.

Emmelie Simic

Stockholm, June 2018

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1. Introduction

Additive manufacturing (AM) also known as 3-D printing, is a technology in which components usually are built by a layer upon layer technique. It is characterized by adding material with different methods, such as powder or wire instead of subtracting material from a raw part [1]. The production takes place in a digitally controlled step, where no molds or other tools are required. From the industry perspective, AM technologies have the potential for significantly impacting traditional production models in terms of industrial machinery, assembly processes and supply chains [2]. The main advantage with AM is that it can be quickly converted to produce different unrelated products and also very complex geometries. The technology has been used primarily for prototype manufacturing, but now also for commercial products in the industry such as aerospace, military, medicine motorsports and dentistry [3, 4]. Today the most common methods to manufacture components are injection molding and infusion for polymers and usually casting for metals. Using these conventional methods over AM normally takes longer time.

The Swedish Defense Materiel Administration (FMV) is an administration that supplies the Swedish armed forces with materiel. Therefore it is in its interest to investigate if it is possible to use AM for field repair and maintenance in, for example, Mali and Afghanistan. Although AM has developed in the civilian sector, the European Defence Agency has considered that there is great potential for this technology to improve the defense capabilities. Among them are mobility, sustainability, power and protection, for example field repair and field maintenance and reduced logistic burden [4].

There are others who have looked over the potential. The Norwegian counterpart to FMV called FFI has developed a 20-foot standard container with a workshop of AM to be able to bring this to field. Such containers are easy to transport and handle. They had a two week trial during the main winter exercise Cold Response 2016. Two aspects that were tested were prototype development and spare parts production. A total of 32 different prototypes were designed and produced, and the conclusion from the field test was that AM is an excellent prototyping tool and that it is in fact possible to produce spare parts in-field with AM today [5].

The Swedish armed forces uses very complex defense equipment and systems such as uniforms, GPS, computers, tanks, ships, boats, aeroplanes and ammunitions and with that some sort of rifle is also needed [6]. When equipment is used over time it tends to break. This is why the Swedish armed forces is severely impaired without spare parts in field.

Some of the systems that are used can be old, meaning that spare parts are scarce or even that there are no spare parts at all in stock (*information is taken from TIA GoF, it is a product that FMV uses to provide basic and management data for the materiel*). A possibility is also that the spare parts are produced with methods and techniques that no longer are available on the market or legal to use from an environmental point of view. Another aspect is that the original equipment manufacturer may no longer support the system, and that the technical data is no longer available or useful. Since the availability of computers was not common before, there is a risk that the drawings were made and outlined in 2D on paper.

Tailoring is also an interesting aspect, since, as the military contains both men and women, the physical sizes of the soldiers are more diverse than ever. If personal equipment can be individualized to maximize safety, performance and prototypes for product improvement at a reasonable cost AM would be even more interesting for FMV.

1.1 Purpose

FMV wants to obtain more knowledge about AM and clarify whether it is possible to use the technology for field repair and maintenance. The task of this work is to investigate how the quality and performance of additively manufactured spare parts differs from conventional spare parts of the assault rifle AK5C.

The following assignments have been defined in order to fulfill the purpose:

- Make an investigation about additive manufacturing
- Find a suitable additive manufacturing process that can be used to manufacture the three spare parts: hammer axis, gas cylinder and the magazine follower.
- Make a functional evaluation of the spare parts in the AK5C and analyze the parts before and after the evaluation, according to strength and quality.

1.2 Method

To approach this project, a background study will take place to gather information about additive manufacturing and the assault rifle AK5C. This will be collected through published articles, technical literature and descriptions and related internet sources. Based on the technical requirements and the components, a method will be chosen and described in more detailed. 3-D models will be created, and the components will be manufactured with additive manufacturing. A functional evaluation of the printed components will be executed and analyzed.

2. Background

In this section, relevant background information is presented to provide a deeper understanding about the assault rifle AK5C, which contains the components that have been chosen for this project, and also about additive manufacturing and its principles.

2.1 Design and working principle of the assault rifle AK5C

The Swedish soldiers' primary armor has always been the firearm, and in the armed forces the soldiers are using the assault rifle AK5C, figure 1. It is a rifle with a 5.56 mm caliber and is known for its high safety functions and its durability. Most of the modern assault rifles that are used today are manufactured in steel, alumina and plastics. This is because they are cheap materials easy to get hold of. The rifle has multiple settings, which will affect the hammer axis and gas cylinder in different ways, whereas the magazine follower will only be affected when it brings up the last bullet in the magazine where the cartridges are kept [7].

Figure 1. The AK5C rifle, being the Swedish soldiers' primary armor [7].

When the rifle is loaded, there is a cartridge in the chamber. This is the initial state before firing. In this state the loading mechanism is fully performed and the bolt is sealed against the barrels locking block. To fire off the rifle the trigger has to be pressed. During this, the hammer turns toward the backside of the firing pin, figure 2. The pin is pushed forward and lights the cartridges primer.

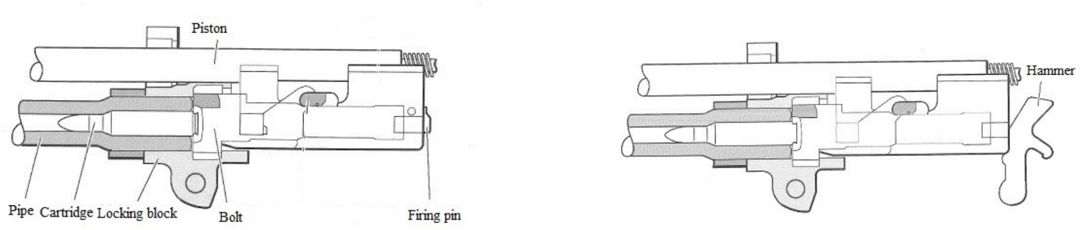

Figure 2. The State before firing (left), and the state when the hammer is positioned on the backside of the firing pin (right) [7].

2.1.1 Semi-automatic and automatic firing

There are two fire modes that can be used for the rifle AK5C: semi-automatic and automatic. The position of the selector lever on the rifle separates the two. For semi-automatic fire, the lever is in position P, whereas for automatic fire, it is in position A, figure 3. Semi-automatic fire is when firing one round at a time, and automatic fire means firing several rounds at a time. These two settings will affect the assault rifle differently. For semi-automatic fire, the hammer is released and thrown against the rear part of the spark plug, the spark plug is pushed forward and the cartridge fires, figure 3. After that the hammer is brought back to the tightened position where it is hooked up by the hammer latch, figure 3 (left) [7].

Automatic fire has almost the same principle, except that the hammer of the rifle is against the rear of the spark plug during the whole time when firing until the trigger is released. Then the hammer is brought back to the tightened position the same way as for semi-automatic firing. Since the hammer-axis works as an axis for the hammer to rotate around, it is more affected during semi-automatic than automatic firing. This is because for every round that is fired in semi-automatic, the hammer goes back and forth around its axis, causing friction and wear, whereas for automatic fire, it only goes up every time the trigger is pressed [7].

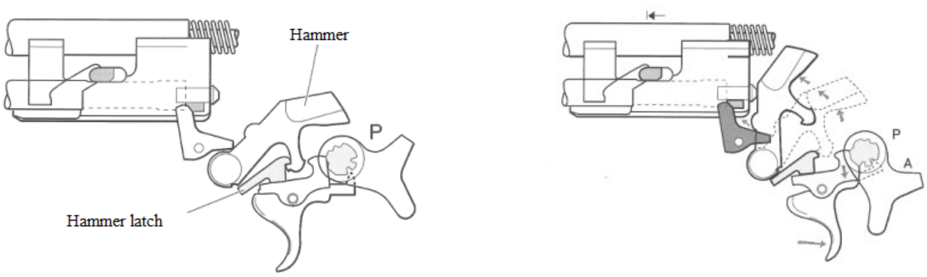

Figure 3. Initial state where the mechanism is locked and the hammer is locked by the trigger bar at the front [7].

When the cartridge is fired the projectile is pressed forward trough the barrel. When the projectile has passed the barrels gas channel, part of the gas flows through the gas block to the piston head where the piston is pressed backwards and where the rifle is then reloaded, figure 4. The piston head is placed inside of the gas cylinder, so the gas cylinder is being exposed to heat and pressure from the gas on the side of the piston as well as on its inside by the gas from the fired projectile. This gas is the gas that is used to reload the rifle during automatic fire [7].

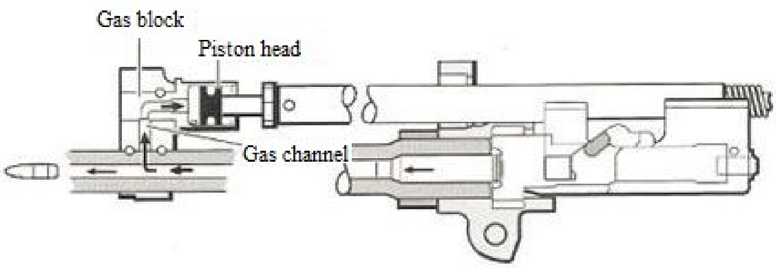

Figure 4. Movement when the cartridge has just left the barrel and the mechanism moving backwards, reloading the rifle [7].

2.1.2 Specification of technical requirements

Technical requirements for the assault rifle AK5C were set from the beginning when FMV ordered it from the producer/supplier, and for the rifle as a system, with all the components included. The most important requirement is that the metals have to be free from slag inclusions, cavities and hardeners that may affect the safety, function or strength of the rifle. Furthermore, they need to be corrosion resistant since the rifle has to be able to handle saline air that otherwise may affect the functionality and safety, or require new surface treatment. The rifle should function in the temperature range of -40 to +40°C. The components in the rifle must have a lifetime of at least a thousand rounds, and must also be able to be cleaned with chlorine lubricants or hot water. [8]

These requirements, table 1, will therefore be guiding for which type of additive manufacturing that will be chosen but also the different materials for the components.

Table 1. Technical requirements on the rifle and its components [8]

Requirements	Specification
Material	Free from slag cavities or hardeners
Corrosion and oxidation resistant	Saline air
Working temperature	-40 ℃ to + 40 ℃
Lifetime	10 000 rounds
Chemical resistance	Chlorine
Water	Temperatures up to +95 ℃

2.2 Components of the assault rifle AK5C

2.2.1 Hammer axis

Around the hammer axis, a hammer is positioned. The hammer axis, figure 5, is to enable the hammer to be brought against the firing pin (see 2.1). During this motion, the hammer is making a quarter turn around its axis. The hammer is then brought back to the starting position again. During this whole movement, the hammer axis is being exposed to friction which leads to wear. FMV believes that this eventually causes the hammer axis to break [9-10].

Figure 5. The hammer axis

The hammer axis is made of a high-strength steel that has the designation 34CrNiMo*S*6 (as can be (see figure 1 in appendix). This is a steel that is usually used in the construction industry for gears and axles that are exposed to high stresses. It advantageously combines high ductility, deep hardenability, toughness, strength and is corrosion resistant [11]. The 34CrNiMo*S*6 steel corresponds to 34CrNiMo6 but has a controlled sulfur content, which provides improved machining properties [12]. For mechanical properties, see table 2.

Table 2. Mechanical properties for the material 34CrNiMoS6 [11-12].

Yield strength	Tensile strength	Elastic modulus	Hardness
700 MPa	900-1050 MPa	208.9 GPa	270-325HB

2.2.2 Gas cylinder

The gas cylinder, figure 6, surrounds the piston in the rifle, which is being pushed backwards by the gas pressure when a cartridge is being fired. When the projectile passes the gas duct, part of the gas is going up through the gas block to the piston head and the piston is being pushed backwards. During and after the process, gas leaves the rifle trough the holes that can be seen in figure 12 and some of it is going on the sides of the piston and inside of the gas cylinder to create air cushions to prevent friction between them. During the process, the gas cylinder is subjected to pressure and heat which put high demands on the material [7].

Figure 6. The Gas cylinder.

The gas cylinder is manufactured in X5CrNi18-10 (see figure 2 in appendix). It is a stainless austenitic chromium-nickel steel which has high ductility, good weldability and mechanical properties, table 3. The austenitic stainless steel has good corrosion resistance in most corrosive environments and the material is usually used in components like tubes and pipes, fittings, flanges and accessories and can handle very low and high temperatures [13].

Table 3. Mechanical properties of X5CrNi18-10 at room temperature [14-15].

Yield strength (20°C)	Tensile strength	Elastic modulus	Hardness
200 MPa	500-600 MPa	200 GPa	160-200HV

2.2.3 Magazine follower in the plastic magazine

The magazine follower in the plastic magazine pushes up the last cartridge in the magazine. A magazine contains 30 bullets also referred to as rounds. When 29 bullets have been fired, the magazine follower pushes up the last bullet in correct position in the cartridge mode in the rifle. In addition, it is used to stabilize the other bullets in the magazine and to hold them in place after every bullet has been fired [7].

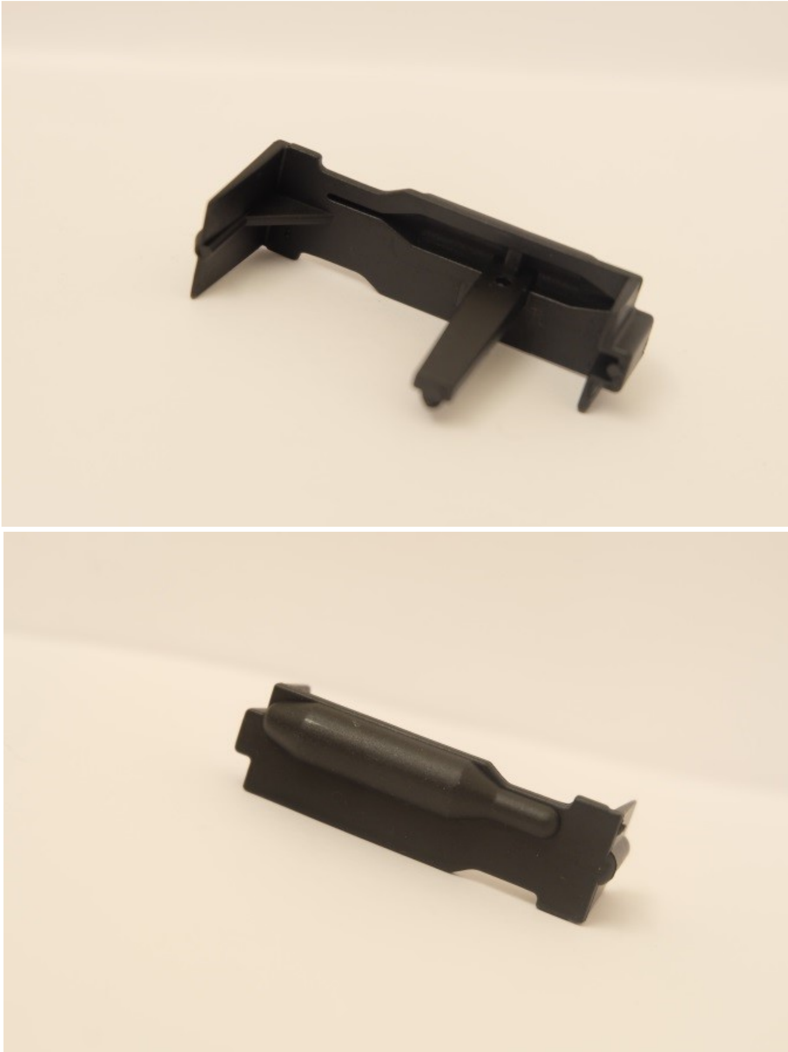

Figure 7a-b. The magazine follower from two different angles.

Glass fiber reinforced polyamide 6.6 (PA6.6 -30% gf) is a composite that contains 30 % of reinforced glass-fiber. This type of material is known for its stiffness, toughness and resistance to dynamic fatigue. Compared to unreinforced components it offers improvements in mechanical properties, table 4, and it also competes with metals in many engineering applications because of the ease of fabrication, light weight, economy, and mechanical and thermal properties, table 3 [16].

Every time the last bullet in the magazine is pushed up in the cartridge, the upper part of the magazine follower is subjected to friction. To mitigate this, an even and smooth surface is required. The magazine follower is manufactured in glass fiber reinforced polyamide 6.6 (PA6.6 -30% gf) as can be seen in figure 3 in appendix, and has been injection molded to get the shape and structure necessary, figure 7.

Table 4. Mechanical properties at room temperature for the composite 30-33 % glass-fiber reinforced polyamide 6.6 [16].

Yield strength (elastic limit)	Tensile Strength	Elastic modulus
120-150 MPa	110-140 MPa	6.1-7.6 GPa

2.3 Additive manufacturing

Additive manufacturing was first patented in 1984 by the scientist Alain Le Mehaute [1]. It is a well-known technology and it is characterized by the addition of material, usually a layer-by-layer with different methods such as powder or wire instead of subtraction of material from a raw part. In the beginning, AM was used within the preliminary and first step of the design phase of a product, this because of the reduced production costs and the short time to provide a prototype. In recent years this technique has also been considered and used in low-scale mass production because of the advantages the technology possesses [1].

Additive manufacturing is standardized in the US (ASTM F2792) and in Germany (VDI 3405), and is commonly used worldwide [17]. The technology has opened up the construction of evolutionary shapes which means structures with designs that are impossible or difficult to build via conventional machining.

AM makes it possible to build components with complex geometries and materials with added functionalities such as internal cooling channels and internal lattice structures [18]. This type of functionalities are quite difficult to fabricate with conventional manufacturing processes. Components that are manufactured trough an AM process is usually in need of minimal or no post processing, and the produced parts can be used directly [18].

With the AM technologies available today, it is possible to build components with different types of materials such as metals, polymers, and ceramics. AM is not only used in several industry applications such as aerospace, automotive, medical, machinery, building constructions and electronics but it is also used in consumer applications as jewelry, fashion and in food industry [18].

2.3.1 Characteristics of AM

There are some characteristics that are defined for additive manufacturing in general [17].

- The geometry of each component is obtained only and directly from a CAD (computer aided design)
- There are no tools needed during the manufacturing-step except the 3D-printer
- The properties of the material for the component is generated during the building process (for example powder or wire)

- The components can be built in any direction, you do not have to fix and secure the parts with a clamp which also takes away the risk to destroy a component. But some of the parts needs support structures and the orientation of the support can affect the properties of the component.
- All AM processes can be run using the same STL data, which is the conversion of the CAD.

2.3.2 The typical process steps in additive manufacturing

Using additive manufacturing there is a number of steps involved, it starts from the CAD description to the physical resultant part, figure 8. There are eight general steps and they usually apply to all AM technologies since AM is not a "push button" technique. There is of course some variation depending on the method that is being used and also the design of the particular component. Some steps can be involved for some machines but may be irrelevant for others [19].

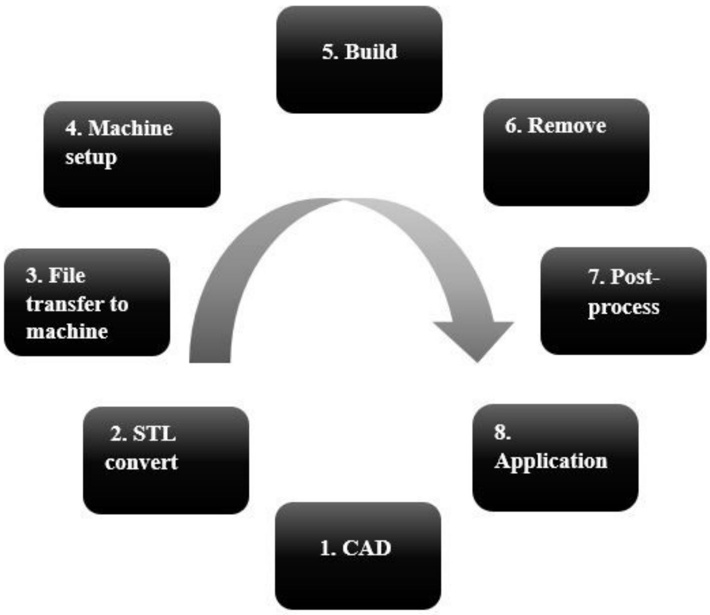

Figure 8. The figure shows the sequence of the eight general steps when using additive manufacturing, redrawn from [19].

1. **CAD:** In order to use additive manufacturing, there must be a software model that fully describes the external geometry of the part that will be manufactured trough AM. It is also possible to create a 3-D surface representation from an existing part using a 3-D scanner such as magnetic resonance imaging or a laser.

2. **Conversion to STL:** To be able to use the CAD file in the AM machine, the file needs to be converted to an STL file format. The file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices (layers).

3. **File transfer to AM machine**: The file has to be transferred to the AM machine in order to build the desired part.

4. **Machine setup:** Some settings must be made to be able to build the component. Building parameters such as material constraints, energy source, layer thickness, timings, resolution are some of the things that may need to be addressed.

5. **Build:** Building of the part in the machine is an automatic process. After the machine setup is done, and the STL file is transferred to the AM machine, the component can almost be built without any control. Only monitoring is needed to ensure that no errors have occurred during the building process like running out of material or power, or because of software glitches etc.

6. **Removal:** When building of the component in the AM machine is complete, it has to be removed which will require interaction with the AM machine.

7. **Post processing:** Components that have been built in an AM machine may sometimes require to be built with support material; this is because it is very hard to build something on a flat surface. The support has to be removed after the process and the parts have to be cleaned before they are ready to use.

8. **Application:** At this step the parts may be ready to use, but some parts need additional treatment before they can be used in the intended application.

2.3.3 Categories/Methods of additive manufacturing processes

There is a wide variety of different AM processes available and individual processes which vary in their method of manufacturing, depending on the material and the technology of the machine. In 2012, a standard terminology for additive manufacturing was formulated by the American society for testing and materials (ASTM) into 7 categories [20].

Vat Photopolymerization

Vat photo polymerization is an additive manufacturing process that uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. To be able to cure or harden the resin where an ultraviolet light is required (these materials undergo a chemical reaction and becomes solid), this is done while a platform moves the object downwards after each new layer is cured. An example of a method that includes Vat photo polymerization is: Stereolithography (SLA). [20]

Material Jetting

Material jetting is an additive manufacturing process that creates a 3-D object in a similar way as a two-dimensional ink jet printer. The material is deposited layer by layer onto a building platform using either continuous or drop on demand that solidifies, a method called: Drop on demand (DOD). [20]

Binder Jetting

Binder jetting is a process that uses two types of materials: a binder and a powder. The binder, which is usually in liquid form, works as glue for the powder between and within the layers, and the powder gives the component its structure and rigidity. To manufacture the component a print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. The component that is being printed is lowered with the build platform after each layer so a new layer can be deposited [21].

Material Extrusion

Material extrusion is a process where the material is drawn through a heated nozzle and deposited layer by layer. The nozzle can move horizontally and the component that is being printed is lowered with the building platform on completion of a layer so a new layer can be deposited on top. It is a quite commonly used technique that is used on many inexpensive, domestic and hobby 3-D printers. A typical method is: Fused Deposition modelling (FDM). [20]

Powder Bed Fusion (PBF)

Powder bed fusion is an additive manufacturing process that either uses laser or an electron beam to melt and fuse material powder together for every layer. A laser/electron beam fuses the first layer of the model together. After this, a new layer of powder is spread across the building platform using a roller and the new layer is being fused until the component is complete. All powder bed fusion processes involve the spreading of the powder material over previous layer. Several methods, some for metals and some for polymers, are based on this technique: Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Direct Metal Laser Melting (DMLM), Selective Laser Melting (SLM), and Selective Laser Sintering (SLS). [22]

Sheet Lamination

Sheet Lamination is an additive manufacturing process that uses sheets of material which are bound together to form an object. It is possible to either use metal or paper but then the manufacturing processes look a little bit different. But either way, laminated objects are often used for aesthetic and visual models and are not suitable for structural use. The methods included here are Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). [23]

Directed Energy Deposition (DED)

Directed energy deposition is an additive manufacturing process that has a more complex printing process It is commonly used to repair or add additional material to existing components.

It consists of a nozzle mounted on a multi axis arm which deposits melted materials in either wire or powder form onto the specified surface, where it solidifies. It is similar to material extrusion, but the nozzle can move in multiple directions and is melting the material with a laser or an electron beam as a thermal source. Methods included here are Laser engineered net shaping, Directed light fabrication, Direct metal deposition, and 3-D laser cladding. [24]

PBF (powder bed fusion) seems to be the method most suited for this work, since there will be two parts printed in metal and one part printed in a polymer. PBF seem to be the most appropriate process for metal, but also for the magazine follower that will be manufactured in a polymer, this because of the complexity and the tolerances required. A general description on how to choose an additive manufacturing method will follow, so will a description of PBF.

2.3.4 How to choose an additive manufacturing process

With an ever increasing number of different additive manufacturing methods, machines and technologies available, it is important to know which method to choose. Since there are a lot of methods on the market, it has become more and more difficult to choose from among them. To be able to choose the method that will give the best result of the manufactured component with the required characteristics and material properties, one can follow a process selection criteria step. It is a process that will follow a number of steps to be able to choose the most suitable process method, figure 9 [25].

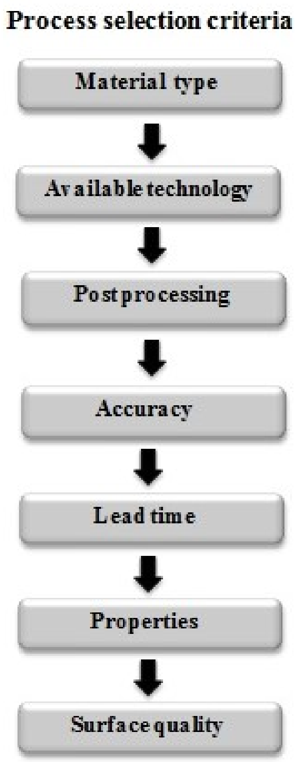

Figure 9. Criteria steps to choose the most suited additive manufacturing method for the component that is going to be manufactured with AM, redrawn from [25].

Material type

The material that the component will be manufactured in plays a very important role in deciding which type of AM process that will be used. In this case there are three components that will be manufactured, two in metal and one in polymer. That means that the selection of AM method must be based on the mechanical properties of the materials that the three components are originally made in. If the originally material does not exist on the AM market another material has to be selected that can meet the requirements.

Available technology

After deciding the material for the components, a consideration must be done to see which process that can give the best result for the type of 3-D body that is going to be manufactured. In this case, the process must be able to produce a defect free component without slag, cavities and/or hardeners so it does not affect the safety, function or strength of the rifle badly. Some processes are able to produce defect free components, but with some of the processes it may not be possible for certain material types. For material 316L, for example, there is no defined industrial parameters to use in EBM to produce a defect-free component.

There are also some processes that use binders as adhesives which are not suitable for structural applications such as aerospace or automobile parts since they may lead to porosity, as it can do in conventional sintering processes. A good choice when it comes to strength requirements, defect levels and structural applications is for example SLM. This is something to have in mind when making the decision in which method that is the most suitable one for the component that will be manufactured trough AM [25, 26].

Post processing

Depending on the AM method that will be used and what the component will be used for, there will be more or less post-processing of the component. For example, when processing metals with SLM the components will experience high residual stresses. To solve this, support structures are required.
Another thing is surface treatment. This is needed to obtain the surface quality that the components might need since some of the surfaces can become quite rough when they are manufactured with AM. Heat treatment, coating and some machining might be needed as well, depending on the requirements of the component [25, 27].

Accuracy

In AM there is a wide range of accuracy capabilities. Some processes have accuracies around 1 mm and others are capable of sub-micron tolerances. Usually, it is said that the larger the building volume and the higher the build speed, the worse the accuracy. This is notable, for example, in beam deposition processes, where the slowest and most accurate beam deposition processes have accuracies approaching a few microns. For larger bulk deposition machines there are accuracies of several millimeters. This has to do with the machine architectures, lack of closed loop process monitoring and control strategies. There is also a material dependency in accuracy that includes shrinkage and residual-stress-induced distortion. It is important to choose a process that can handle this type of problem, since the accuracy is quite important for the parts that will be manufactured in most of the cases [25].

Lead time

AM makes it possible to manufacture shapes that previously were impossible to manufacture or could only be realized using manufacturing methods with long lead time tools. AM is not only a good option when it comes to really complex geometries or shapes, it is also a good option when it comes to production of small series, uncertainty in size of the series, and high shape requirement, as well as when a short lead time is important. Even if AM is considered to have better lead time than conventional manufacturing there is still a variation of lead time between the different processes. Take the PBF processes as an example. It is a quite slow process, since the process takes place inside of a chamber that has to be heated and filled with inert gas. Except that it also has to be cooled down after the building process inside of the chamber is completed [28][29]. Meanwhile, for Binder jetting, it is the post-processing that takes time instead. The post-processing for Binder Jetting includes several steps such as curing, de-powdering sintering, infiltration, annealing and finishing.

When it comes to making a decision regarding which method that will be used for the component it will rather be a decision on which method that can give the component the best properties more than a decision based on the lead time [25].

Properties

The components that will be manufactured by AM require different specific service conditions which plays an important role in choosing the right AM process. Also, the material properties that are required for particular service conditions influence the selection of the fabrication process, for instance the strength requirements and the amount of defects [25].

Surface quality

In AM, surface quality is another concern. With some techniques, the surface gets rough if large powder particles are used. In theory, this can be fixed, but it will severely hamper the flowability of the powder, and so its ability to spread into a uniform layer on the substrate. The surface quality requirements play an important role in deciding the right fabrication process [25].

2.3.5 Powder Bed Fusion

The Powder bed fusion processes were among the first commercialized additive manufacturing processes. It is a method where thin layers of powder are applied on a build plate. When a layer is completed, a new layer of powder is applied and the process continues until the model or the component is finished. The source that fuses the powder together and determines the shape is usually a laser or an electron beam, and it fuses on locations specified from the CAD data of the model. Selective laser sintering (see figure 10) was one of the first PBF processes that were commercialized. Other processes that involve PBF have been modified from the basic approach in one or several ways to enhance machine productivity, enable different material to be processed, and/or to avoid specific patented features [30].

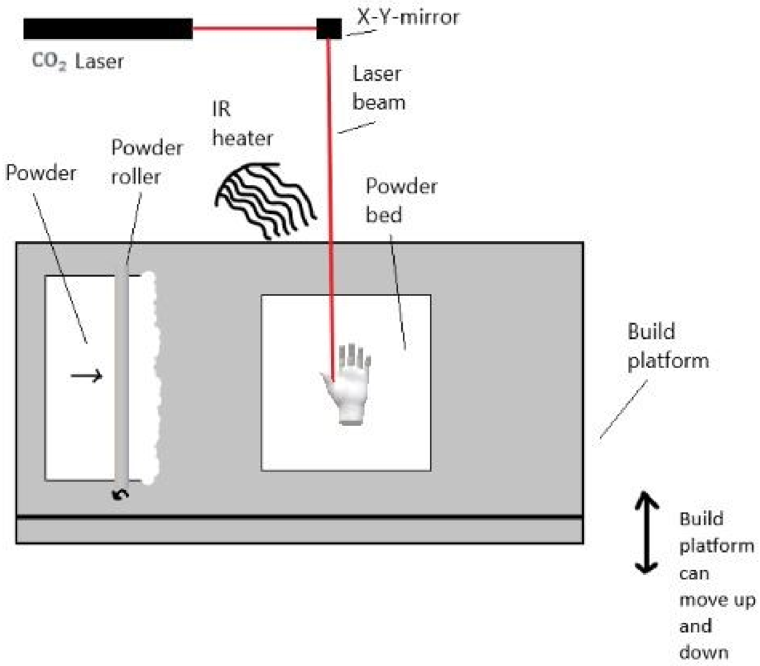

Figure 10. The setup of a selective laser sintering machine, redrawn from [30].

From the beginning, the laser sintering processes were developed to produce prototypes made in plastics. Today it is possible to produce parts with a broad range of materials with properties comparable to many engineering-grade polymers, metals and ceramics. Because of this, the PBF processes are used increasingly worldwide and are also used for direct manufacturing of end-use products [30].

Almost all materials that can be melted and solidified can be used in PBF processes, for metals a good candidate is if it can be welded. The most common materials that are used in PBF processes are thermoplastic polymers that are called polyamides and also known as nylon. For metals, it is stainless and tool steels, titanium alloys, nickel-based alloys, aluminum alloys and cobalt-chrome alloys which will be described later [30].

2.3.6 Advantages and disadvantages with the PBF process

Using PBF as an AM process have both its advantages and disadvantages. PBF can for example process a very wide variety of materials compared to other AM processes. It is possible to process semi crystalline polymers, amorphous polymers, metals and also some ceramics that are commercially available. Internal cooling channels and other complex features that would be impossible to machine are possible by using PBF [29].

A drawback with PBF, is that for most of the methods for metals, it requires support material, because when processing metals, a high residual stress can unfortunately be experienced in the material. To avoid the material from warping, the support material is added. This, in turn, unfortunately leads to expensive and time-consuming post-processing of components made in metal. Because of this, it is really important how the part is oriented and the location of the support in the build chamber. Polymers, on the other hand, do not need any support structures, which also means that many parts can be produced in a single build and improve the productivity [29].

Another problem with the PBF process, is the surface finish, since the size of the powder determines the finish of the surface. The larger the particles of the powder, the rougher the surface, and, correspondingly, the smaller the particles of the powder, the finer the surface. Larger size of the particles affects the surface finish, minimum feature size and minimum layer thickness, it is of course possible to use smaller particles but it can be spread and harder to handle.

With a PBF processes, the total time of the production of the part can be longer than other processes and it has to do with the preheat and cool-down cycles that is needed in the PBF processes [29].

PBF methods that use polymer-based laser sintering is commonly used for prototyping and end-use applications in many industries. They are competing with injection molding, infusion and other polymer manufacturing processes, and the processes are competitive for low-to-medium volume with geometrically complex parts. While metal based processes including laser and electron beam are one of the fastest-growing areas of AM around the world. Metal PBF processes are becoming increasingly common for aerospace and biomedical applications, due to their inherent geometric complexity benefits and excellent material properties when compared to traditional metal manufacturing techniques [29].

2.3.7 Description of the methods within powder bed fusion

Like all other technologies in AM, the PBF technology has a lot of terms when it comes to the different methods. The methods included in PBF are divided into three groups depending on which thermal source that is being used and type of binding mechanism, which varies depending if the material is melted or sintered.

With sintering it means that the powder is fused together and that it creates a metallurgical binding without reaching melting temperature. While for melting, the powder is fused together and creates a metallic bond when the powder is reaching a temperature where it is melting. Laser sintering is referred to as LS and laser melting is referred to as LM. [30].

The powder bed fusion methods are known as selective laser sintering (SLS) which was the first commercialized PBF process, selective laser melting (SLM), direct metal laser sintering (DMLS) and electron beam melting (EBM) and has been named after different AM manufacturers such as EOS, 3D systems, Arcam and Renishaw and SLM solution (see figure 11) [31]. Polymer laser sintering (pLS) and metal laser sintering (mLS) machines are quite different from each other. Current metal powder bed fusion additive manufacturing systems tend to use melting as opposite to sintering to build full-density parts.

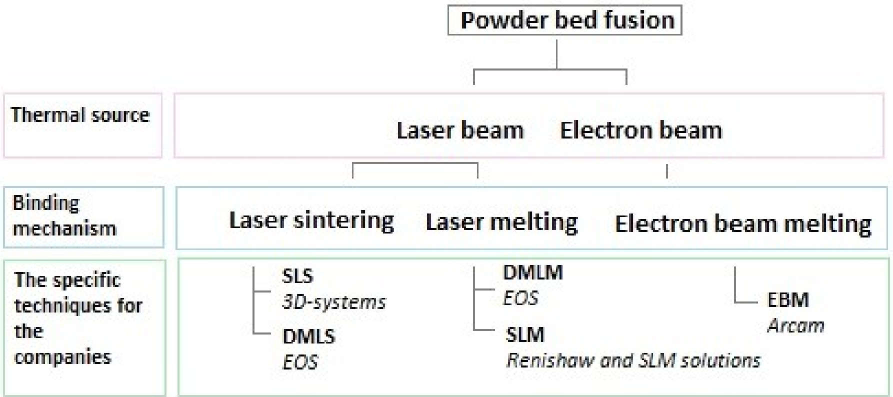

Figure 11. Thermal sources, binding mechanisms and the specific techniques for each company and method.

Laser Sintering

Laser sintering is an additive manufacturing technology that is quite popular, especially for service parts. To use a laser as a thermal source to densify a powder bed selectively has been widely researched and has been applied to metals, ceramics, polymers and composites. The use of the term sintering has been used in a misleading manner because the predominant densification mechanism has been shown for most applications to be melting and reflow. The Definition for laser sintering according to ISO/ASTM is that the process produces objects from powdered materials using one or several lasers to selectively fuse or melt the particles at the surface, layer upon layer in an enclosed chamber [32]. If one compares sintering with traditional powdered metal sintering where a mold is used and heat and/or pressure, so for laser sintering the word is only used because it is an historical term and unfortunately a misnomer.

SLS is a process within powder bed fusion that is classified as a laser sintering process, DLMS used to be classified as that as well. In the beginning, the DLMS process was based on liquid phase sintering mechanism involving partial melting of the metallic powder, but today the process uses full laser melting.

SLS was developed at the University of Texas by Carl Deckard in 1987. It is a three-dimensional printing process having an moderate to high speed, where the surface finishes and accuracy vary between moderate and good. The first machine was commercialized in 1992 by DTM Corporation, and ever since the SLS process has found applications in various industries with the use of many materials, also in 1994 the company EOS developed an SLS machine [33].

The solidification process in SLS is obtained by fusing or sintering selected areas of the successive powder layers, this is done by using thermal energy supplied through a laser beam.

The materials that were the first to be used more widely in SLS are polymers, in this case thermoplastic such as polyester, nylon, polyvinylchloride (PVC) and etc. [34]. With SLS, it is possible to deposit powder layers with a thickness that ranges between 20 and 150 µm. The commercial machines for SLS differ in the way the powder is deposited (roller or blade), or in the atmosphere (Ar or N2) but also in the type of laser that is used [35].

Process parameters like laser wavelength, laser energy and powder characteristics (particle size, powder composition and mixing), affect the resulting surface quality or part density.

Laser Melting

A mechanism that is most commonly associated with PBF processes is laser melting, also called full melting. Full melting usually processes engineering metal alloys and semi-crystalline polymers. In this type of materials, a full region of material is exposed to thermal heat source (laser or an electron beam) and is melted to a depth exceeding the layer thickness [36]. Before starting the building of the next layer, the scan of the laser or electron beam re-melts a portion of the previously solidified structure. Either next or above the just scanned area. This type of melting is very effective because it creates a well-bonded, high density structures.

A material that can be used is for example a polymer like nylon polyamide, for a semi-crystalline material like this DLMS has a distinct melting point and a possibility to produce parts with the highest possible strength. Examples of metals that can be used are the engineering alloys of titanium, stainless steel and CoCr [37]. Full melting of these results in unique properties that are distinct from, and are sometimes more desirable than, cast or wrought parts made from identical alloys. Processes that are the most common ones for laser melting is selective laser melting (SLM) and DMLS [30].

In 1995, the first metal laser sintering machine was introduced by EOS and was named DMLS to distinguish the technology from selective laser sintering. This was a machine that could process metallic powders with a liquid phase sintering (LPS) approach. But EOS introduced many different other materials and machine models, including platforms for foundry sand and full melting of powders. Sometimes the terminology is confusing, even though the process term DMLS is used by the company EOS today, the process causes full melting.

To get really good part quality or to know how to get good part quality, it must be known how the part is affected by the powder material, exposure parameters as well as inert gas flow and temperature at the building platform. If wrong parameters are used, porosity can arise and also lack of fusion and rough surfaces [38].

The assurance of the quality of the parts for DMLS consists of several technologies. For example monitoring of the machine, laser parameters, camera based inspection of the powder bed and diode based in-process monitoring of the melting process [38].

2.3.8 Material characteristics for PBF and mechanical properties

Metals

Aluminum $AlSi10Mg$

Aluminum is a light metal that can be used in motorsports and aerospace applications. It has good casting and thermal properties, and can be used for parts subjected to high loads. The parts can be machined, spark eroded, welded, micro shot-peened, polished and coated. Because of the good casting properties, it is also typically used for cast parts that have thin walls and complex geometries [39].

Titanium $Ti64$

Titanium is a light metal with really good mechanical properties and corrosion resistance. It has high purity and also very good bioadhesion. It can be used in aerospace applications, motorsports, functional prototypes and biomedical implants [40].

Maraging steel MS1

MS1 is a martensite-hardenable steel that has excellent strength and high toughness and hardness. The parts are easily machinable after the building process and they have good polishability. The typical application areas are tooling, mechanical engineering and aerospace [41][42].

Nickel alloy Inconel718

Inconel 718 is a nickel-based alloy characterized by high heat resistance and outstanding corrosion resistance, and it also shows high performance with respect to tensile strength, fatigue, and creep at temperatures up to 700°C. This material is ideal for high-temperature applications such as gas turbines parts and the power and process industry [43].

Stainless steel 316L

The stainless steel 316L is a steel that can be used in many areas, for example watches, jewelry and in the medical field for surgical aids. It has high ductility and excellent corrosion resistance, is possible to post-process, and meets the requirements for surgical implants [44].

Stainless steel CX

CX is a stainless steel that is characterized by having exceptional corrosion resistance, high strength, really good hardness and it is easily machinable and easy to polish. An application for this type of steel is injection mold tools for corrosive plastics, for example in the medical and food industry and also industrial applications where high strength and hardness is required [45].

Polymers

PA2200 – Nylon 12

Polymer 12 can be used for functional parts, medical applications, and plastic parts of high functionality. It is characterized by its high strength, fatigue resistance, chemical resistance, low creep, low friction and also thermal stability [46].

PA1101 – nylon 11

Nylon 11 is characterized by its high strength, fatigue resistance, chemical resistance, low creep and low friction. This material is based on renewable resources and can therefore be classified as environmentally friendly. PA1101 can be used in applications that require high ductility and high impact resistance [47].

For mechanical properties of all the materials described above, see table 5.

Table 5. The Mechanical properties of each material that has been described above [39-47]

Metals					
Material	**Tensile strength** [MPa]	**Yield strength** Rp 0,2% [MPa]	**Young's modulus** [GPa]	**Hardness**	**Density** [g/cm^3]
AlSi10Mg					
Horizontal direction (XY)	460 ± 20	270 ± 10	75 ± 10	119 ± HBW	2.67
Vertical direction (Z)	460 ± 20	240 ± 10	70 ± 10		
Ti64					
	1290 ± 80	1150 ± 80		320 ± 15 HV5	4.41
MS1					
Horizontal direction (XY)	1200 ± 100	1100 ± 100	150 ± 25	33-37 HRC	8.0 – 8.1
Vertical direction (Z)	1100 ±150	930 ±150	140 ± 25		
Inconel 718					
Horizontal direction (XY)	1060 ± 50	780± 50	160 ± 20	30 HRC	8.15
Vertical direction (Z)	980 ± 50	634± 50		287 HRC	
316L					
Horizontal direction (XY)	640 ± 50	530 ±60	185	89 HRB	7.9
Vertical direction (Z)	540 ± 55	470 ± 90	180		
CX					
(1)	1080	840			7.9
Polymers					
PA2200					
Horizontal direction (XY)	48		1.65		0.93
Vertical direction (Z)	42		1.65		
PA1101					
Horizontal direction (XY)	48		1.60		0.99
Vertical direction (Z)	48		1.60		

(1)The numbers are average values and are determined from samples with horizontal and vertical orientations.

3 Materials and methods

3.1 Design

3.1.1 CAD models

Two out of the three CAD models, figure 12 and 14, have been made in the CAD program Autodesk fusion 360. The CAD model for the gas cylinder, figure 13, was received from SAAB in Östersund.

For the 2-D drawing that was received for the magazine follower, the technical data was not complete, so additional measurements had to be made to get a complete 3-D model. The process involved dimensional measurements with a Vernier-caliper from Mitutoyo on a physical spare part manufactured with traditional manufacturing.

As mentioned earlier, many of the systems that the armed force uses are quite old. The drawings of the spare parts are only made in 2D and outlined on paper, together with technical data, like the material and the dimensions. Even if the CAD model for the gas cylinder was received from SAAB, a comparison with the 2-D drawing and the CAD model was made to verify that all the measurement and dimensions were correct for the CAD model.

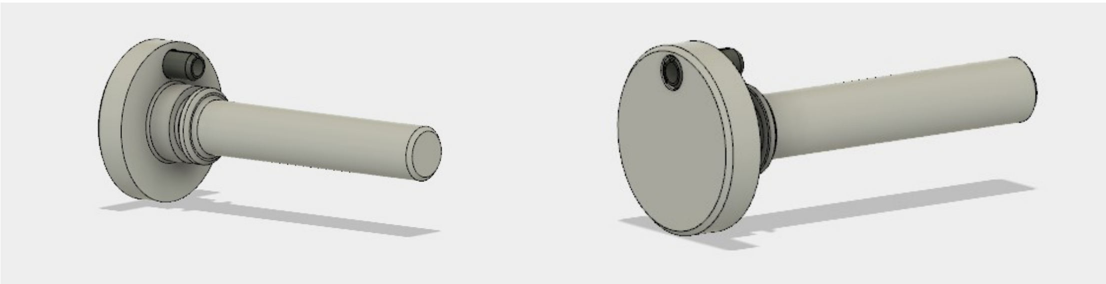

Figure 12. Hammer axis from two angles.

Figure 13. Gas cylinder from two angles.

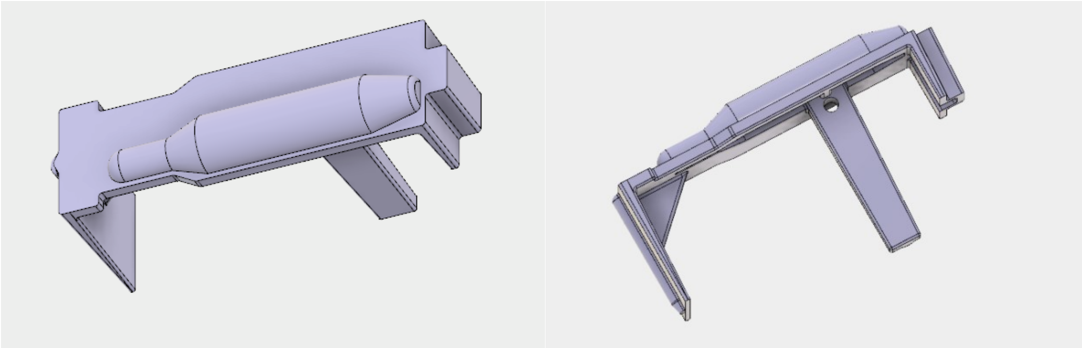

Figure 14. Magazine follower from two angles.

3.2 Manufacturing

The spare parts were manufactured by Lasertech LSH AB in Karlskoga.

When the 3-D models were finished, a prototype of the magazine follower was ordered to verify that all the measurements were according to the traditional manufactured part. The Magazine follower was tested in the magazine to verify that its dimensions were correct and that it did fit as it should. Some design changes were made, but nothing critical. After this, the 3-D files were sent to Lasertech, where two hammer axis, four magazine followers, and two failed and two successful gas cylinders were manufactured with the specific AM method and materials.

3.2.1 Selection of AM technique, method and material

For the metal components, DLMS with the machine EOS M 290 was chosen, whereas for the polymer component, SLS with the machine EOS P 395, was chosen. See table 6 for characteristics.

Table 6. Characteristics for the machines EOS M 290 and EOS P 396 that was used for [48-49].

Machine	EOS M 290	EOS P 396
Building volume	250 mm x 250 mm x 325 mm	340 mm x 340 mm x 600 mm
Laser type	Ytterbium-fiber laser 400 W	CO2, 70 W
Precision optics	F-theta-lens; high speed scanner	F-theta-lens; high speed scanner
Scan speed	Up to 7.0 m/s	Up to 6 m/s
Variable focus diameter	100 um	
Power supply	32 A	32 A
Power consumption	Max 8.5 kW/ typical 3.2 kW	Max 10 kW, typical 2.4 kW
Building speed	Depends on the material	48 mm/h

The hammer axis was made of an iron-based alloy called maraging steel MS1, even though the stainless steel 316L would have been a better choice due to the technical requirements. The gas cylinder was made of a nickel-based alloy called Inconel 718, and the magazine follower was made of the polymer PA 2200, also called nylon 12. The materials are described in 2.3.6.3, and the specific building parameters such as particle size, layer thickness and building speed can be seen in table 7.

Table 7. Specific building parameters for the three parts manufactured.

	Hammer axis [41]	**Gas cylinder[43]**	**Magazine follower[46]**
Material	Maragin steel MS1	Inconel 718	PA 2200
Particle size	20-50 µm	20-50 µm	20-50 µm
Layer thickness	40 µm	40 µm	120 µm
Building speed	15.1 mm/h	0.014 mm/h	35 mm/h

3.2.2 Post treatment

After receiving the finished 3-D printed parts, the hammer axis and the gas cylinder had to go through some post-processing since some details in the parts were not possible to print. This is because the resolution was not good enough. In the hammer axis, for example, there is a thread which is difficult to 3-d print with good enough precision and accuracy. Instead it had to be machined with a lathe. Also, the small pin that can be seen in figure 12 needed to be attached afterwards, and were ordered and cut to the right dimensions at the workshop at The Ångström Laboratory, Uppsala University.

In the gas cylinder, a pin had to be attached in the small hole that can be seen in the CAD model, figure 13. Inside, a spring was attached with a small pointed rod together with the pin. In addition, some edges were polished so the parts could fit perfectly in the rifle AK5C.

3.3 Functional evaluation

The shooting experiment was conducted according to the technical provision F1303-901060, which is a method description for evaluation of strength and wear resistance of the AK5D [48], which is just an updated model with a shorter shaft than the AK5C, but works just the same. The method description refers to determination of the rifle's strength, durability and precision properties of sustained firing [50].

A ballistic testing equipment was set-up to go through with the functional test, figure 15, it is an equipment that is set-up to be able to have the rifle in so one know that the bullets goes in the same position all the time), cooling-system for the rifle, container for empty sleeves, fire speed detection device, and equipment for control, bullets and magazines (see table 8).

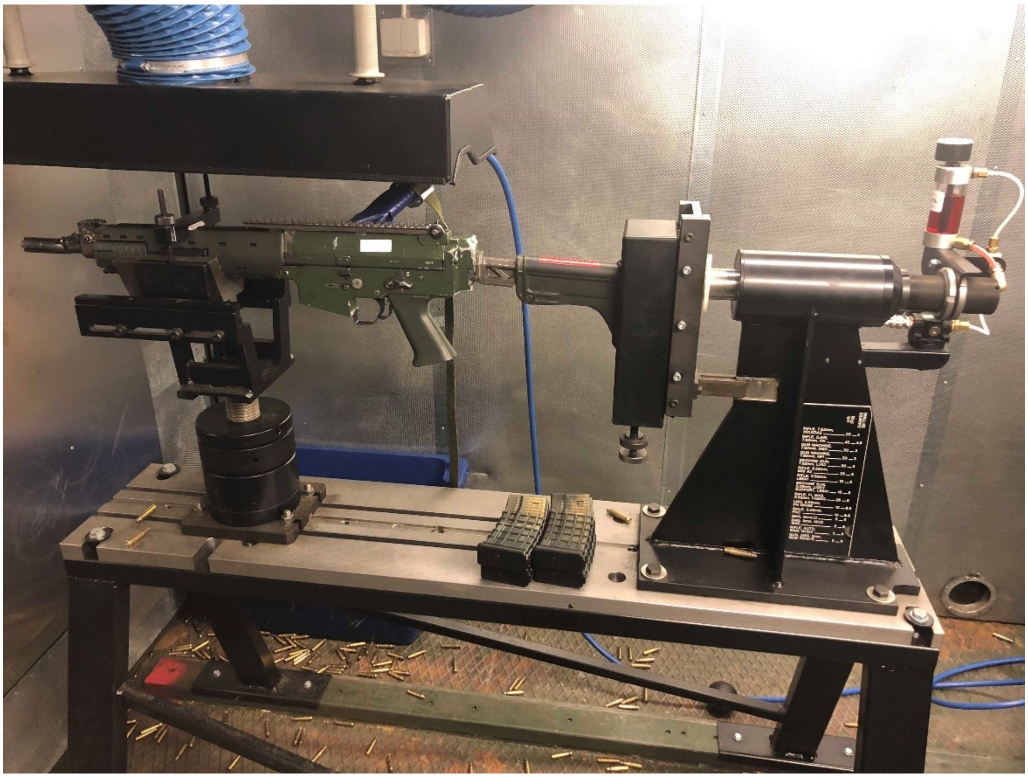

Figure 15. Test set-up, ballistic testing equipment from Evridge engineering company limited.

Table 8. Hardware used for the functional evaluation of the additively manufactured parts.

Amount	Materiel
1	Ballistic testing equipment 1980-DRGPF7057GA
4	Plastic magazines
1	AK5C
2000	Bullets (5,56 mm caliber)
1	Cooling system
1	Fire speed detection device

According to the technical provision, a series covered 100 rounds given in a sequence that can be seen in table 9.

Table 9. The order that the firing was made according to the technical provision.

Order	Amount
1	10 rounds semi-automatic
2	10 rounds automatic
3	20 rounds semi-automatic
4	30 rounds, fast double rounds
5	30 rounds, short point rounds of 3-5

1000 rounds were fired for the hammer axis and 500 rounds for the magazine follower and for the gas cylinder, 1000 rounds of shooting with semi-automatic were done. The test sequence could not be followed in this case, see table 10.

Table 10. The amount of sequence and how many rounds for each component that was evaluated.

Component	Sequence	Rounds
Hammer axis 1	10	1000
Hammer axis 2	10	1000
Gas cylinder		1000
Magazine follower	5	500
Magazine Follower	5	500
Magazine follower	5	500
Magazine follower	5	500

Measurement of the firing speed was made with a magneto speed V2 chronograph. It is primarily used for measuring the output velocity of the projectile but it also measures the firing speed. Detection is made when the projectile passes two sensors in the same way as a metal detector. The advantage of this one compared to acoustic sensors, is that it has no trouble with echoes.

According to the technical requirements, the rate of fire at +20℃ should be minimum 600 rounds/min [8]. The rate was measured before and after the components were exchanged in the rifle. The firing speed was measured at subseries of 10 rounds automatic fire with a fire speed detection device that was attached to the barrel.

After the technical evaluation, the components were weighed and measured to see if there was any loss in material or if wear had occurred. The components were also evaluated in a microscope.

4 Results

4.1 Result of the manufactured components of AK5C

It was possible to manufacture the parts with additive manufacturing with the methods SLS and DLMS with the materials MS1 (hammer axis), Inconel 718 (gas cylinder), and nylon 12 (magazine follower), figures 16-19.

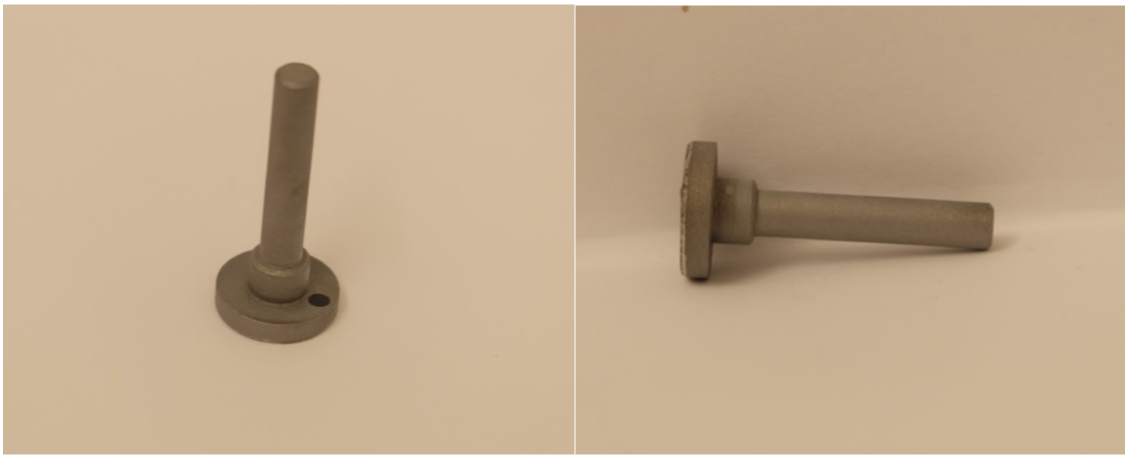

Figure 16. Additively manufactured hammer axis from two angles with the diameter 5 mm.

Figure 17. Additively manufactured gas cylinder, stopped at half of the intended size with the pipe diameter 18.24 mm.

Figure 18. Additively manufactured gas cylinder completed with the pipe diameter 18.24 mm.

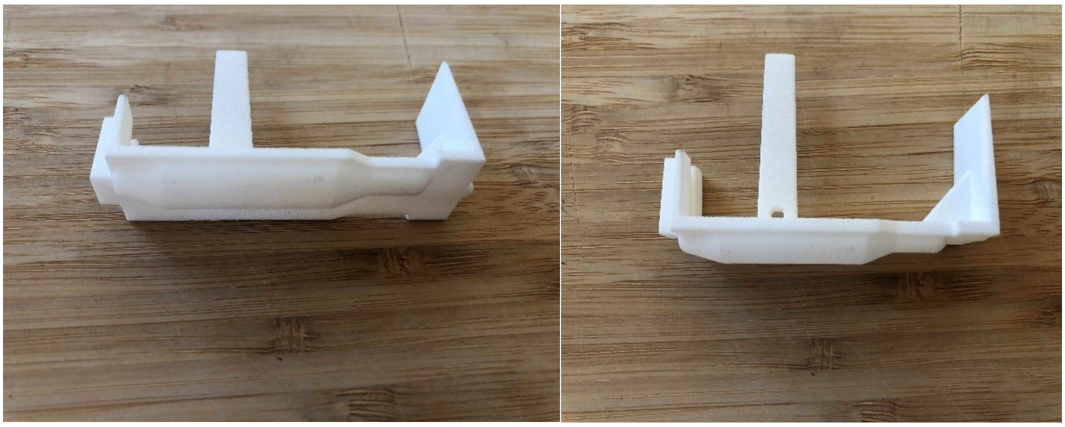

Figure 19. Additively manufactured magazine follower made in plastic.

4.2 Result of the functional evaluation of the additive manufactured components

Both hammer axis 1 and 2 were tested during the functional evaluation and passed the shooting of 1000 rounds without any severe damages. Before and after pictures for hammer axis 1 can be seen in figure 20 and 21.

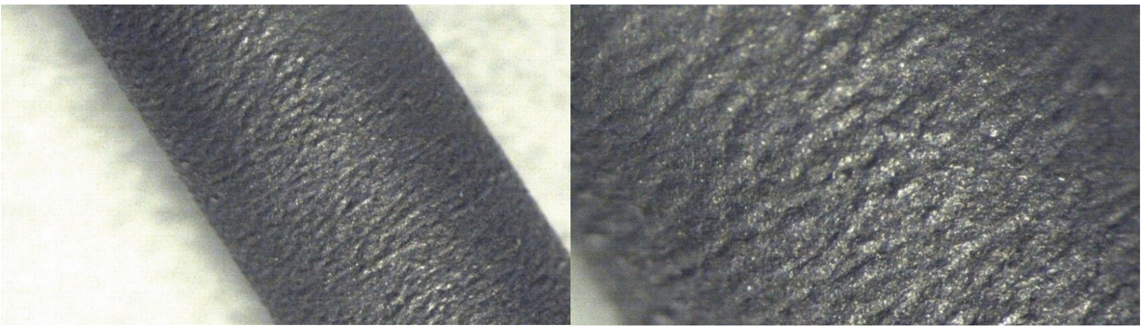

Figure 20. Additively manufactured hammer axis 1 before the shooting of 1000 rounds with the diameter 5 mm taken with a stereo microscope from Zeiss.

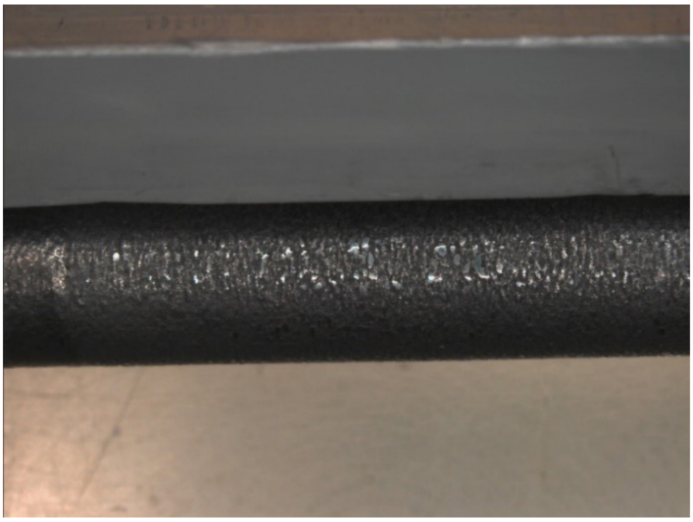

Figure 21. Additively manufactured hammer axis 1 after the shooting of 1000 rounds with the diameter 4.98 mm taken with stereomicroscope Wild M10.

Before and after pictures of the functional evaluation of hammer axis 2 can be seen in figure 22 and 23.

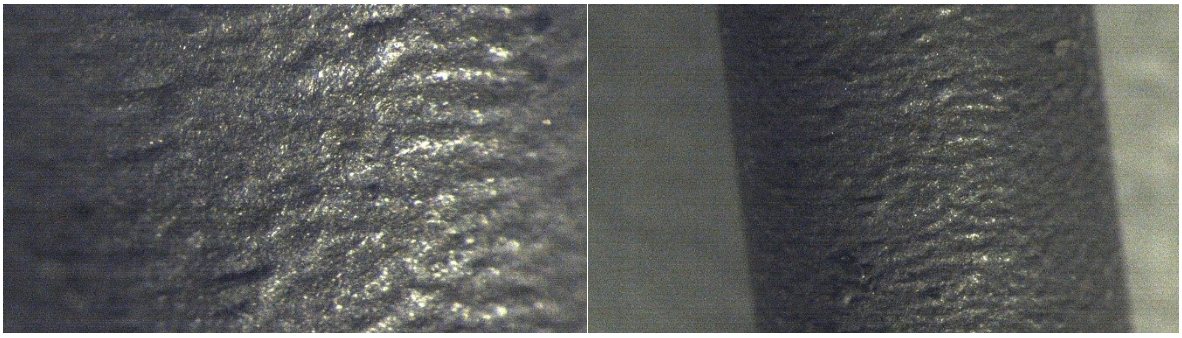

Figure 22. Additively manufactured hammer axis 2 before the shooting of 1000 round with the diameter of 5 mm taken with a stereo microscope from Zeiss.

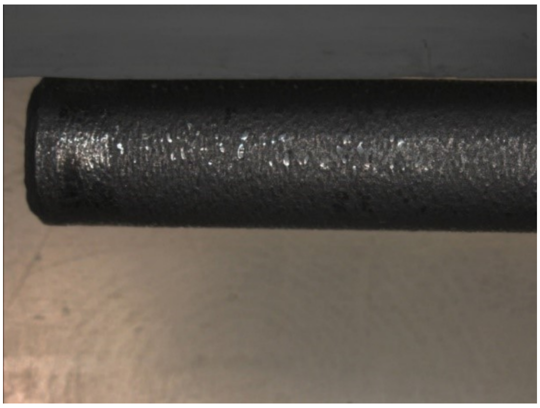

Figure 23. Additively manufactured hammer axis 2 after the shooting of 1000 rounds with the diameter 4.98 mm on the hammer axis taken with stereomicroscope Wild M10.

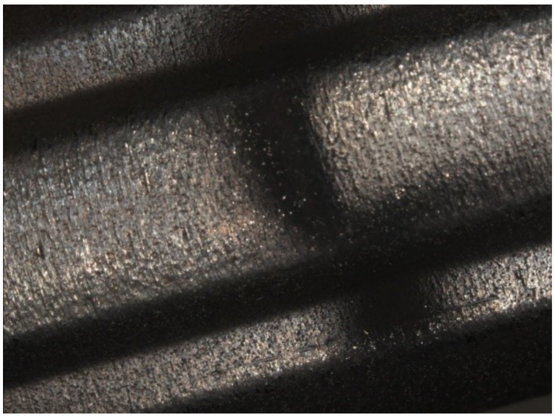

Figure 24. Additively manufactured gas cylinder after the shooting of 1000 rounds with the pipe diameter 18.24 mm taken with stereomicroscope Wild M10.

During the shooting experiment of the gas cylinder, it was only possible to fire 1000 rounds with semi automatic fire.

Four plastic magazines were used during the shooting experiment, which means that four conventional plastic magazines got exchanged to four additively manufactured ones. Before and after pictures were chosen for only one of the magazine follower, figure 25 and 26.

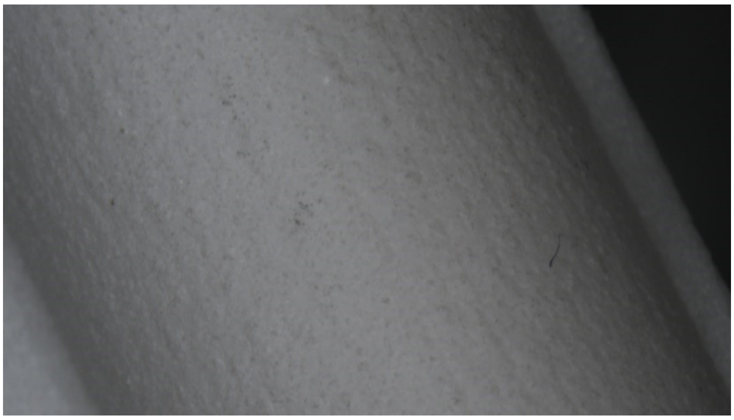

Figure 25. Additively manufactured magazine follower before the experiment was performed, with the diameter 5,56 mm of the cartridge on top taken with a stereo microscope from Zeiss.

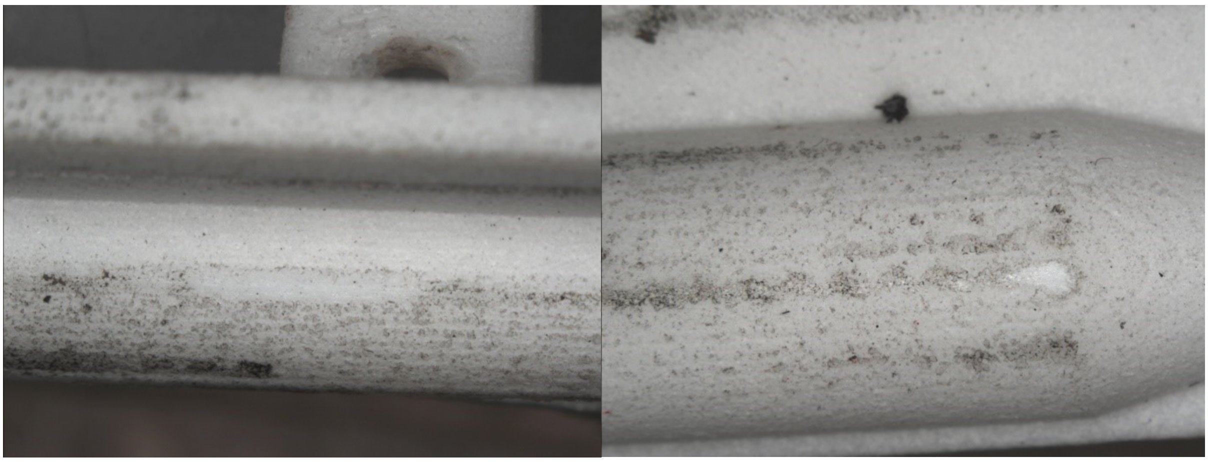

Figure 26. Additively manufactured magazine follower after the shooting of 500 rounds, with the diameter 5,56 mm of the cartridge on top taken with stereomicroscope Wild M10.

4.3 Result of the measurement and weight

In table 11, the dimensions and weigth can be seen for hammer axis 1 and 2, gas cylinder and the four magazine followers before and after the shooting evaluation.

Table 11. Weight and diameter before and after shooting with the additively manufactured parts.

Manufacturing method	**Weight [in gram]**		**Diameter [in millimeter]**	
	Before	After	Before	After
Additive manufactured parts				
Hammer axis 1	9.073	9.038	5.00	4.98
Hammer axis 2	9.073	9.022	5.00	4.98
Gas cylinder	106.654	107.599	18.24	18.24
Magazine follower 1	4.132	4.063	N/A	
Magazine follower 2	4.132	4.046	N/A	
Magazine follower 3	4.132	4.108	N/A	
Magazine follower 4	4.132	4.174	N/A	

4.4 Result of the firing speed

The value of the firing speed before and after exchanging the components in the rifle showed different values and it can be seen in table 12. Some of them did pass and some of them did not and this will be discussed in section 5.

Table 12. Fire speed of the AK5C with only conventionally manufactured parts and with an exchanged hammer axis and an exchanged gas cylinder that were additively manufactured.

Conventionally manufactured parts	**Fire speed**
1	618 rounds/min
2	633 rounds/min
Additive manufactured parts	
Hammer axis	
1 (100 rounds)	604 rounds/min
2 (200 rounds)	599 rounds/min
3 (1000 rounds)	639 rounds/min
Gas cylinder	
1	595 rounds/min

5 Discussion

5.1 Additive manufactured parts

The result of the additive manufactured components turned out to be very successful. However, there was one problem along the way. The gas cylinder was too long to be able to print at first. In total the gas cylinder is 265 mm and the machine stopped printing at around the half of the length (see figure 17). This was corrected by adding support material through the whole gas cylinder which was removed after the building process in the machine was done. Lasertech thinks this problem has to do with the length of the gas cylinder, it is way too tall and the walls are way too thin so the material started to clog in the middle of the process and the machine stopped the printing at the height of 145 mm.

During the removal of the support material, a miscalculation was made, which made the inner-diameter of the cylinder become larger then it was supposed to be. Instead of 16.84 mm, it became 17.03 mm. This was noticed during the functional test when the gas cylinder was placed in the AK5C.

In 3.2.1, it is mentioned that the margining steel MS1 is the material chosen for the hammer axis, even though the stainless steel 316L would have been a better choice due to technical requirements. This is because one of the technical requirements is that the material and the component have to be able to handle corrosion. However, for a functional evaluation the margining steel is good enough. Stainless steel would have required much longer time in the printing machine, which means also a higher cost.

Because of ethical reasons, since the components are part of a rifle, it was hard to find a company that offered to print the components. This caused limitations to which type of material that could be used for the parts manufactured in AM, and also to the type of method.

5.2 Functional evaluation

The functional evaluation went as expected. None of the parts broke and all could handle a test of 500-1000 rounds in a series of 100 rounds given in a sequence except the gas cylinder. As the inner diameter of the gas cylinder became too big when support material was removed, it was not possible to shoot automatic fire, as the gas that reloads the gun in automatic fire leaked out to fast which takes away the pressure inside of the cylinder and with that also the force to be able to reload the rifle again. To strengthen this theory sticky tape in the front of the gas cylinder was used so no leakage of the gas could happened. Four rounds of automatic fire was possible before the sticky tape melted. Hence, for the gas cylinder, it is really important that the inner diameter is correct.

From the functional evaluation, it was possible to see that the shooting had affected the components even though they did not break. In the before and after images that were taken in the microscope it is possible for example to see that some wear has occurred on the hammer axis 1 and 2. In the before, figure 20 and 22, and the after picture, figure 20-23, the wear is quite clear, being the parts that reflect in the image (see figure 21 and 23). What has caused the abrasion is that the material from the hammer and the hammer axis is rubbed against each other way too much during the movement (see 2.1). This can happen if the surface is to rough or the diameter of the component is bigger or smaller. In this case it is possible that it is due to the surface roughness, as the components were not polished or post-treated in any way.

For the gas cylinder, and as mentioned above, it was not possible to shoot automatic fire, but except for that, the functional evaluation was successful. There was some gun powder in the front part of the gas cylinder where the small holes are located which looks like a black stripe see figure 24. At a first glance, it looked like a crack has appeared in the material and gun powder has started to leak out, but in the microscope it was possible to see that was not the case. Instead, gun powder exited the small holes during firing, and got stuck to the cylinder because of the rough surface. It is possible that the same thing happens to the conventional components but since they are manufactured in black it is harder to see if something is stuck on top of the cylinder.

For all four magazine followers, the firing was in total 2000 rounds, but each and every magazine follower were only tested with 500 rounds each. From the image that was taken after the experiment (see figure 26), it is possible to see that abrasion between the magazine follower and the cartridge has occurred, both at the top of the magazine follower and on the side, but since there was no fire arm malfunction, it passed the functional evaluation.

5.2.1 Measurements and weight before and after the functional evaluation

Another thing that has to be taken into account is the weight of the additive manufactured parts. Developing new materiel for the military is often carefully done since a lot of the materiel is going to be carried of the soldiers and also be transported, having too much weight will make it harder for the soldiers to be good and flexible in fight. In the technical requirement the weight is already set from the beginning [8]. There cannot be any changes in weight when comparing conventional and additive manufactured components. The changes for the chosen components are really small so they did not affect the rifle anything but this is something that has to be taken in consideration when other components are printed since the technical requirements are usually very strict.

Since wear occurred at the hammer axis and the magazine follower during the functional evaluation, there will of course be some changes in weight. It has to be taken into account that the before weight is for another piece but the same component. The scale that was used before firing did not give an exact value, so the pieces were weighted again. The gas cylinder and magazine follower number 4 were the only components that gained weight. Looking at the components, it is possible to see that a lot of gun powder got stuck. This is probably the cause of the big change. The rest of the values seem reasonable and can be due to wear.

The diameter of the hammer axis was changed after firing, table 11. It is possible that it has to do with the abrasion as well.

5.2.2 Firing speed

The firing speed was measured before and after the parts were exchanged in the rifle. In table 10, it is possible to see that the firing speed differs a lot for the hammer axis. This is due to friction of the hammer on the axis. In the beginning, the value is close to 600 or slightly under but when it has gone back and forth for about 1000 rounds there has probably been enough wear for it to slide easily so the firing speed went up. Also, for the gas cylinder the fire speed is really low and that has to do with the leakage of the gas that goes out on the sides. The magazine follower did not affect the firing speed.

5.3 AM over conventional manufacturing methods in field

To use additive manufacturing as a manufacturing process in the future for field repair and maintenance is very promising. In this case, it gave almost the same dimensions as the conventional methods, the components were of high quality and didn't break during functional evaluation**.** To use AM in Mali or Afghanistan is probably possible with the method that were chosen here for the parts, but more evaluation and testing are needed.

It is important to understand that many AM machines require careful maintenance, because many of the machines use fragile laser or printer technology that must be careful monitored in an environment that is free from noise and dirt. Even if the machine employs an automatic process, it is important to do regular checks.

Additive manufacturing is not just a "push play" process. To get the best components possible, it is important that the staff is trained to use the machines, from process parameter settings to post-treatment.

5.4 Future perspective

For future work, there are a few things that are really important if FMV wants to be able to use additive manufacturing. In this master thesis, most focus was on to see if the components managed to pass a functional evaluation, but what would happen if the components became really cold or quite warm? Would they still be functional? This FMV should evaluate further.

Another thing is to investigate if it is possible to change the process parameters such as laser beam, the thickness of each building layer, and the powder size to see if the parts can have even better quality than conventionally manufactured ones. It could also be very interesting to see if it is possible to manufacture all metal components in the same material or the plastic parts in one material. Since FMV wants to use AM as a manufacturing method out in the field, it is easier to bring just one or two types of powders.

Yet another interesting area is to look at economic factors, and calculate how much it costs to have different storage supplies in Sweden or just to own a printer and manufacture when the part is needed. Similarly, is it better to have AM equipment in the field or to have it elsewhere and send components there?

The most important part and something that has to be learnt, is to understand that additive manufacturing can be the future manufacturing method. This is why FMV has to start to think future products and weapons shall be developed so that they are AM compatible.

5 Conclusion

In conclusion, additive manufacturing does allow for fabrication of functional spare parts – at least the ones evaluated here. The rifle was fired 1000 rounds with the hammer axis, 1000 rounds with the gas cylinder and 500 rounds with the magazine follower. The functional test for the hammer axis and the Magazine follower was successful without any major changes in dimensions and weight. Except that the diameter for the hammer axis went from 5.00 mm before the functional test to 4.98 mm after the functional test. The gas cylinder on the other hand was both successful and unsuccessful in that way that it was possible to shoot 1000 rounds semi-automatic, but it was not possible to shoot automatic fire without the modification with the tape. There were no sever damages on the components after the evaluation that indicated that they would break even if they would have been tested further more.

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Appendix

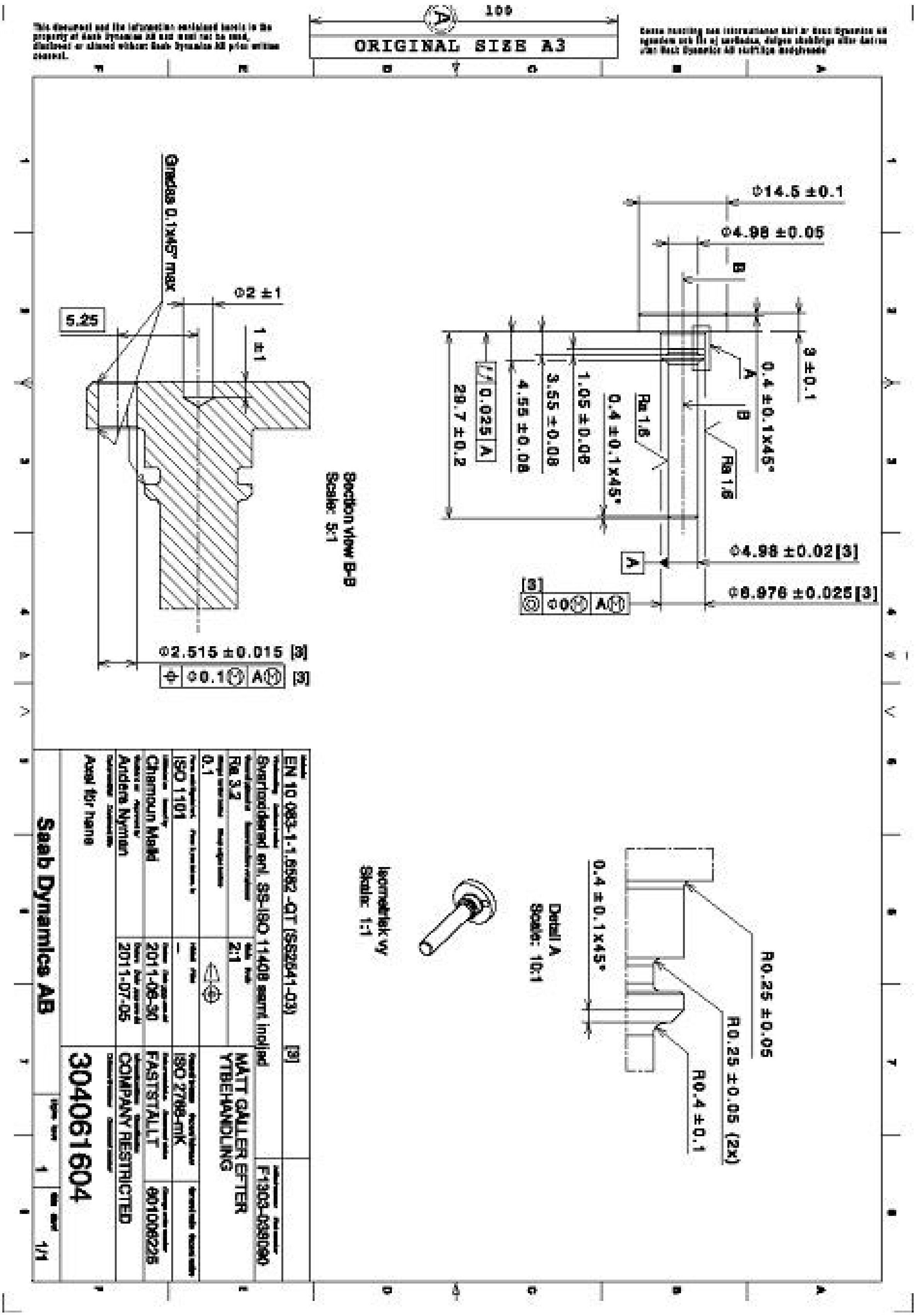

Figure 1. 2-D drawing of hammer axis.

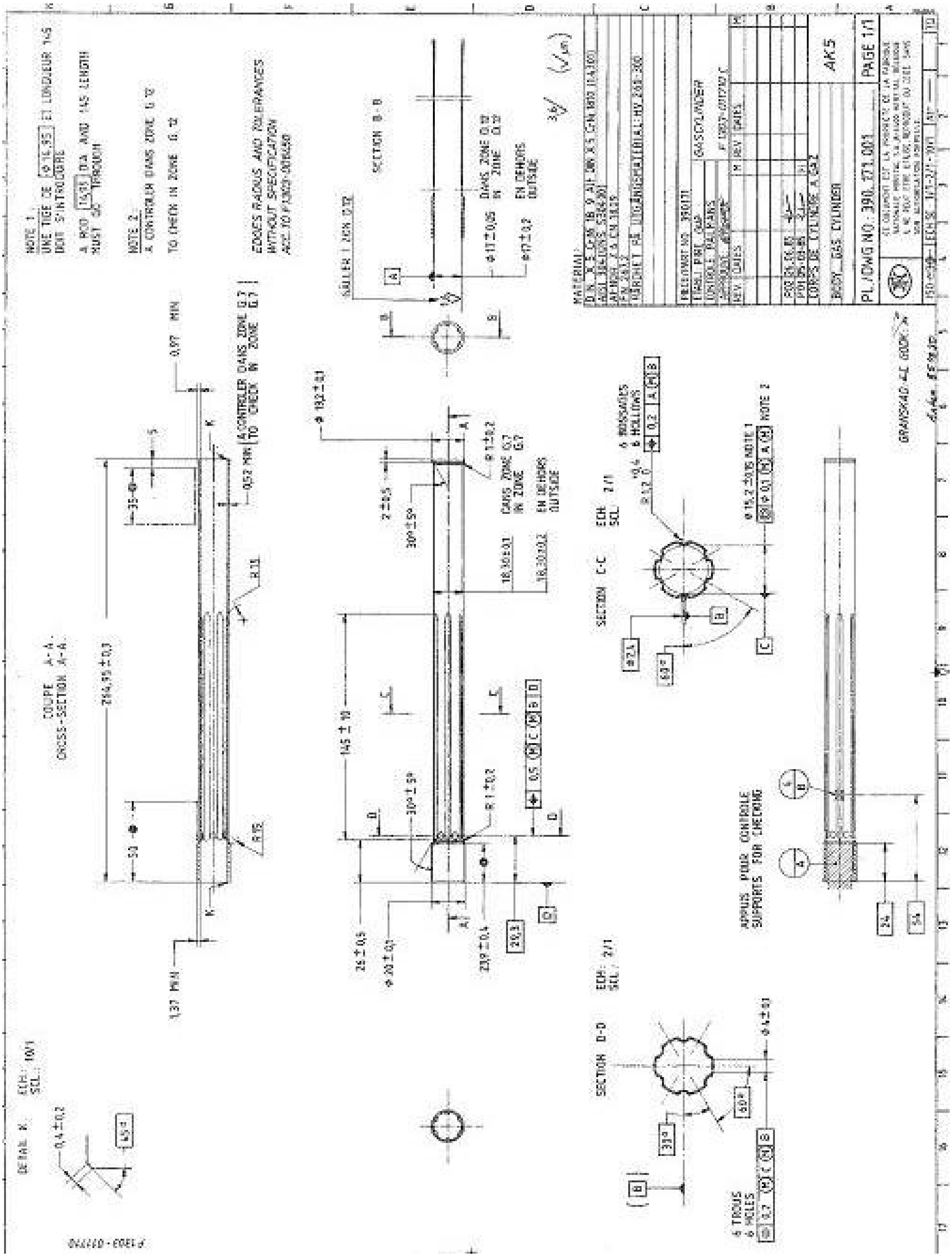

Figure 2. 2-D drawing of gas cylinder.

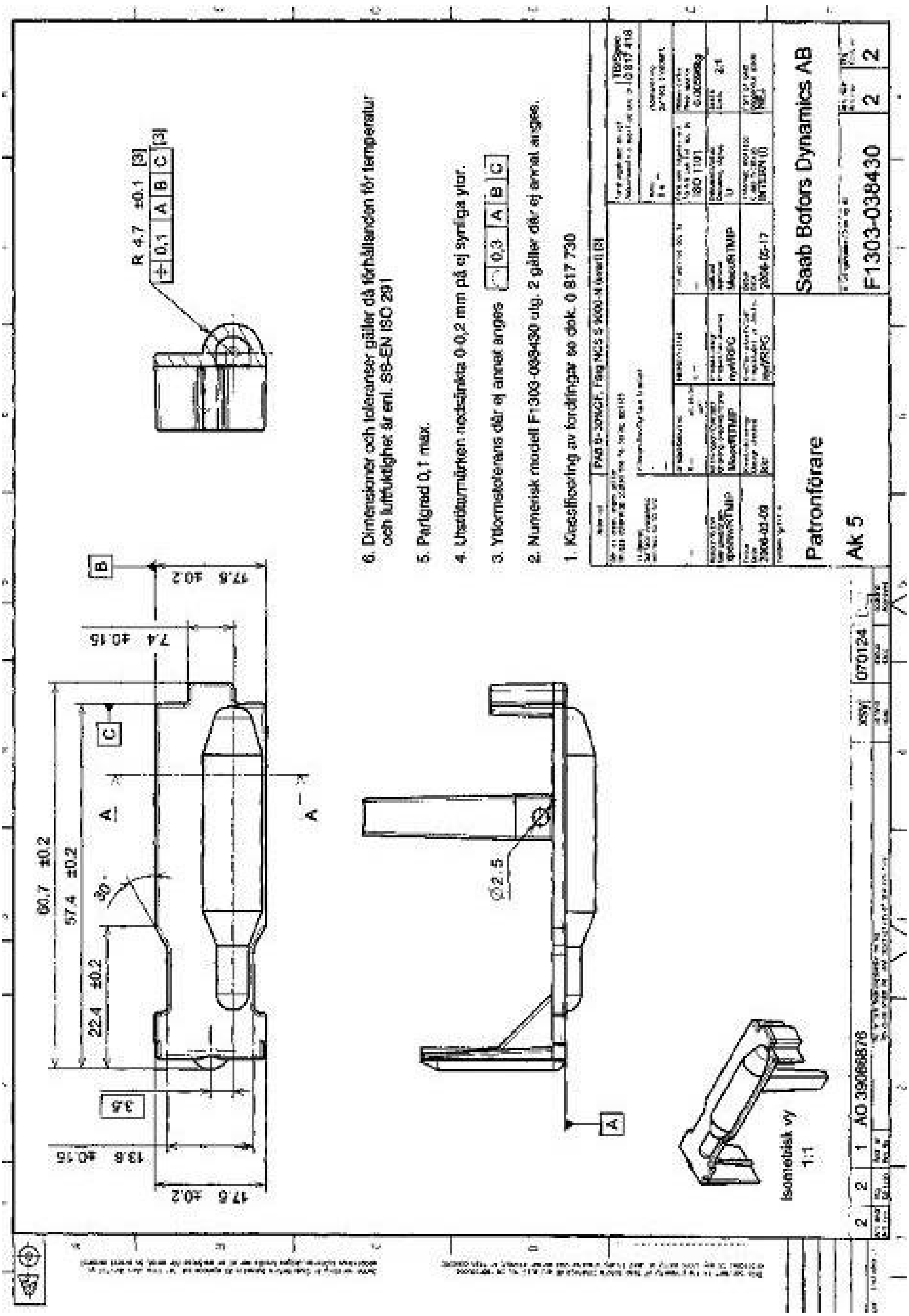

Figure 3. 2-D drawing of the magazine follower and the dimensions of the upper part of it.