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Evaluation of Traditional and Additive Manufacturing Methods of Centrifugal Pump Casing with Regard to Circular Economy

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ABSTRACT

This thesis examines the integration of high-speed machining (HSM) and additive manufacturing (AM) technologies in the production of industrial pump components, with a specific focus on the DCN-19E centrifugal pump casing. The work presents a detailed comparison of these manufacturing methods in the context of the Circular Economy (CE), emphasising sustainability and efficiency. Key aspects include the optimisation of machining processes, toolpath generation and the use of advanced CAM systems such as Autodesk Fusion and Netfabb. The study highlights the potential of AM for rapid prototyping and low-volume production, while also addressing the limitations of each method in terms of energy consumption, material waste and economic viability. The findings contribute to the wider discourse on sustainable manufacturing practices and provide insights into the practical applications and performance evaluation of HSM and AM in the context of modern industrial production.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

HSM	High-Speed Machining
AM	Additive Manufacturing
CE	Circular Economy
CAM	Computer-Aided Manufacturing
SLM	Selective Laser Melting
DCN or MCP	Motor Centrifugal Pump
FDM	Fused Deposition Modelling
EBM	Electron Beam Melting
HPCC	High Precision Contour Control
NURBS	Non-Uniform Rational B-Spline
CNC	Computer Numerical Control
EDM	Electrical Discharge Machining
NDT	Non-Destructive Testing
CT	Computed Tomography
CMM	Coordinate Measuring Machine
EMAT	Electromagnetic Acoustic Transducers
EC	Eddy Current
HPM	High-Performance Machining
ACS	Adaptive Control Systems
HFM	High-Speed Face Milling
TP	Technological Process
CP	Control Program

INTRODUCTION

Rapid advances in manufacturing technologies have created new opportunities and challenges in the production of industrial components. High-speed machining (HSM) and additive manufacturing (AM) have emerged as key technologies, each offering distinct advantages. HSM is known for its precision and efficiency in machining complex parts, while AM, particularly Selective Laser Melting (SLM), offers unprecedented flexibility in design and material usage. This thesis investigates the integration of these technologies in the production of a centrifugal pump housing, with the aim of assessing their effectiveness in the context of the Circular Economy (CE). This research aims to contribute to the development of more efficient and environmentally friendly manufacturing practices.

SCOPE OF WORK

This thesis is divided into three main sections:

Background and theoretical foundations: This section provides an overview of the technical characteristics and operating conditions of industrial pumps, the principles of HSM and an introduction to AM technologies. It also discusses the principles of circular economy, setting the stage for the comparative analysis of HSM and AM.

Technological implementation and processes: This section deals with the practical aspects of HSM and AM, including the selection of appropriate machines, the optimisation of toolpaths and the requirements for CAM systems. The processes are illustrated with a focus on centrifugal pump casings, exploring the advantages and challenges associated with each manufacturing method.

Practical implementation and process optimization: The final section evaluates the performance of HSM and AM in the manufacture of pump casings, comparing their efficiency, material usage and compliance with CE principles. This section also includes a detailed examination of the CAM software used and the implications of these technologies for future industrial applications.

The research concludes with recommendations for optimising the use of HSM and AM in sustainable manufacturing, highlighting the potential for integrating these technologies to achieve better economic and environmental outcomes.

1. BACKGROUND AND THEORETICAL FOUNDATIONS

1.1 Technical Properties and Operating Conditions of Industrial Pumps

Pumps are hydraulic machines used to move liquids such as water, slurry, oil, etc. under pressure. A pump is powered by energy from an engine where part of this energy is lost to overcome hydraulic and mechanical resistance, while the other part is used to create an overpressure that transports the fluid from the pump to its destination.

A centrifugal pump is a type of dynamic vane pump where the working fluid moves in a continuous flow due to the interaction of this flow with the rotating rotor blades and the stationary casing blades. The movement occurs under the action of centrifugal force and has a radial direction perpendicular to the axis of rotation of the rotor. This type of pump is used for both liquids and gases, the latter are often referred to as centrifugal compressors or fans. A 3D model of a centrifugal pump of the ДЦН (Pronounced DCN, translated abbreviation MCP, stands for "Motor Centrifugal Pump") series is shown in Figure 1.1.

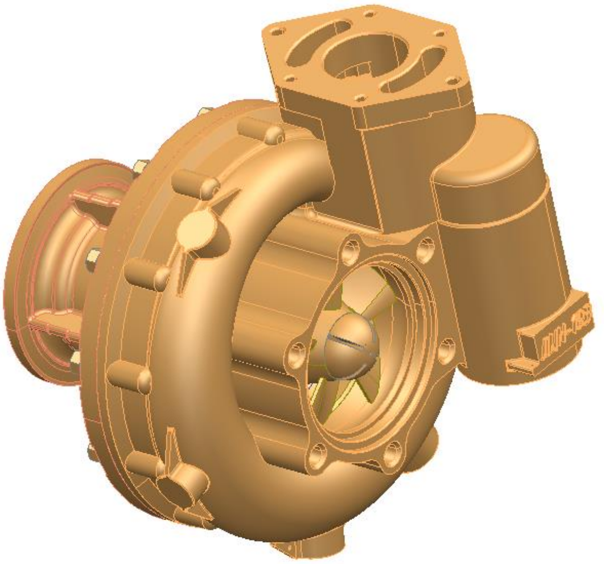

Figure 1.1.1 Volumetric model of a centrifugal pump

The principle of centrifugal pumps is as follows: inside the pump casing, which is usually snail-shaped and spiral, the impeller is rigidly fixed to the shaft. This impeller can be of the open type (disc with blades) or of the closed type, where the blades are placed between the front and rear discs. The blades are usually curved against the direction of rotation of the wheel, forming a logarithmic spiral. The pump casing is connected to the suction and discharge pipes through nozzles.

When the pump casing is completely filled with liquid, the liquid in the impeller channels is thrown from the centre to the periphery by centrifugal force, for example, when the impeller is rotated by an electric motor. This creates a vacuum in the centre of the impeller and increases the pressure at the periphery, which causes the liquid to be pumped into the discharge pipe. Thus, a centrifugal pump continuously moves fluid from the suction to the discharge line.

Centrifugal pumps are available not only as single-stage pumps with a single impeller, but also as multi-stage pumps - so-called sectional pumps. In sectional pumps, the total pressure drop increases in proportion to the number of sections, but the principle of operation remains the same: the liquid moves under the influence of centrifugal force generated by the rotation of the impeller.

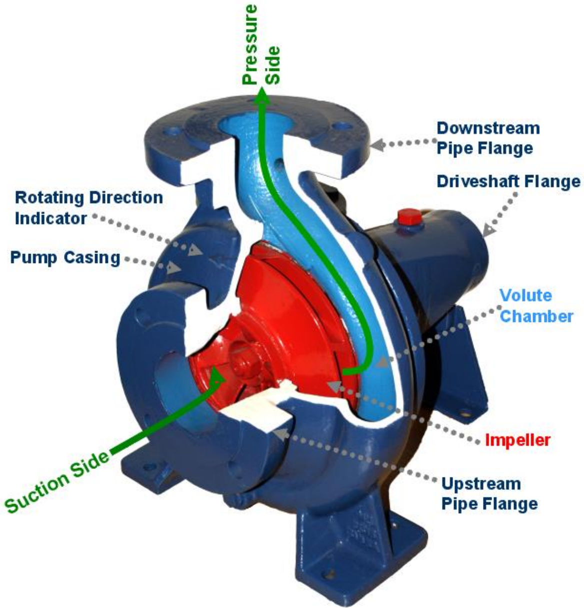

Figure 1.1.2 Schematic diagram of a centrifugal pump in section

Centrifugal pumps are classified according to several parameters:

- Number of stages: Single-stage pumps may have a cantilevered shaft arrangement.
- Location of the wheel axis: Horizontal or vertical.
- Pressure level: Low (up to 0.2 MPa), medium (0.2-0.6 MPa), high (over 0.6 MPa).
- Method of supplying fluid to the impeller: With one-way or two-way inlet, including double suction.
- Type of housing connector: Horizontal or vertical.
- Method of fluid discharge from the impeller: Spiral (liquid is discharged directly into the spiral channel) or vane (liquid passes through a guide device).

- Speed coefficient ns: Low-speed, normal, high-speed.
- Functional purpose: Water supply, sewerage, fire, chemical, alkaline, oil, dredging, thermoregulatory, space, etc.
- Method of connection to the motor: Driven (with gearbox or pulley) or via couplings (magnetic, elastic, other types).
- Location relative to the liquid surface: Surface, deep, submersible.

The efficiency of a pump depends on the speed ratio, operating mode and design. At optimum operation, the efficiency of large pumps can reach 0.92, and that of small pumps can be between 0.6 and 0.75.

The centrifugal pump DCN-19E, equipped with a constant pressure valve and a nozzle, is designed to maintain the specified fuel pressure before the main engine fuel pump. The pump having passing state tests, was put into operation in Ukraine. It is used on passenger and cargo military aircrafts. New models DCN-64 and DCN-72 are being developed on the basis of this pump. The pump is made of AlSi7Mg aluminium alloy (Al-9-T5 DSTU 2839-94) and weighs 2,332 kg. The blanks for the parts are produced by precision casting.

Main parameters and dimensions of the pump:

- Connection points and overall dimensions according to drawing DCN 19-1;
- Motor drive, clockwise rotation;
- Working position at the facility: the pump is mounted to the flange of the motor drive box with the drainage connection facing downwards;
- Long-term operation;
- Working fluid: fuel T-1, TS-1, RT;
- Operating temperature of the liquid from -40°C to +60°C, ambient temperature from -60°C to +130°C;
- When starting the engine, the oil temperature is allowed to be up to -40ºC.

Technical characteristics:

- Minimum flow rate of 800 l/h at 6000 rpm;
- The pump can be repaired according to the technical description and instructions;
- Total weight does not exceed 9.5 kg;
- Average service life before failure is not less than 40,000 hours;

- The service life before the first overhaul, the overhaul period and the assigned maintenance periods are given in Table 1;
- The number of repairs during the specified service life is not limited.

Table 1.1 Resources and service life of the DCN

Product	Resources and service life					
	Until the 1st overhaul		between overhauls		assigned	
	Hours	Years	Hours	Years	Hours	Years
19Э	500	7	500	7	2100	21

The intended shelf life of the pump is 6 years. The average labour intensity to restore its working condition is 22.1 man-hours. Guaranteed parameters of the pump when using fuels T-1, TS-1, RT, at a working fluid and ambient temperature of 25 ± 10 ºC are presented in Table 1.2.

Table 1.2. Parameters of a centrifugal pump

Pump shaft speed, rpm	Altitude above sea level, m	Absolute pressure at the pump inlet kPa, (kgf/cm2)	Pump flow rate, l/h	Overpressure at the pump outlet, kPa (kgf/cm2)
For the product 19E				
3500±50	0	98-373(1,0-3,8)	1500	157-373(1,6-3,8)
8300±50		78-253(0,8-2,6)	45000	451-490 (4,6-5,0)
7000±50	6000	49-304(0,5-3,1)	6000	314-392(3,2-4,0)
5200±50		49-314(0,5-3,2)	1100	304-392(3,1—4,0)
8300±50	7000	49-216(0,5-2,2)	40000	422-471(4,3-4,8)
	12000		32000	383-441(3,9-4,5)
	17000	49-235(0,5-2,5)	12000	331-402(3,4-4,1)
	20000	49-245(0,5-2,5)	8000	324-392(3,3-4,0)

Notes:

1. The pump outlet pressure is measured at the nozzle.

2. A maximum outlet pressure of 784 kPa (8 kgf/cm²) is permitted when the flow rate is changed from maximum to 10,000 l/h within 2 seconds..

Checks include:

- Measurement of valve stem force;
- Pump assembly inspection;
- Run-in;
- Checking the damping properties of the valve;
- Disassembly;
- Acceptance tests;
- Checking the cleanliness of internal surfaces;
- Periodic tests.

1.2 Principles of High-Speed Machining

High-speed metalworking, which allows cutting at extremely high speeds, has become a significant advance in mechanical engineering technology. This progress has been made possible by improvements in carbide grades and new principles in the design and use of cutting tools.

The main types of high-speed cutting include turning, boring, milling, hobbing, planing and drilling. A distinctive feature of all types of high-speed machining is the use of tool materials with increased strength and wear resistance, among which hard alloys and cermets occupy a special place.

The development of high-speed cutting has placed new demands on the machine tool industry and the abrasives industry. Modern machine tools must have the following characteristics:

- Sufficient power, rigidity and vibration resistance;
- A wide range of spindle speeds, mainly electronically controlled for smooth adjustment;
- Extensive use of hydraulic and electrical devices;
- Efficient spindle lubrication and balancing system;
- Availability of a system for automatic chip removal;
- Reliable cooling system for cutting tools;

- Efficient methods of loading and unloading products;
- Pneumatic devices for clamping parts.

These features ensure high productivity and processing efficiency, while increasing the profitability of production processes.

The main requirement for the abrasive industry is the production of a wide range of diamond wheels, which are essential for high-quality sharpening of modern hard alloys.

Observations of the nature of steel chips formed when using cutters with different front angles (+20°, +10°, 0°, -20°) confirm that an increase in cutting speed leads to an increase in the radius of the chip curl. With a chip cross-section of $t \cdot s = 3.0 \cdot 0.1$ mm² and working with cutters with positive angles at low cutting speeds (about 20 m/min), the chips form dense Archimedean spirals. As the cutting speed increases, the chips turn into a spiral ribbon with a coil diameter that increases from 15 to 20 mm at speeds of about 100 m/min up to 50 mm at 300 m/min, making its colour change from light to blue.

When using cutters with negative rake angles at low speeds (approx. 20 m/min), the chips are removed in short curls, while at higher speeds they form a spiral ribbon with a radius of curl that increases significantly faster than that of cutters with positive rake angles. For example, at negative angles of $\gamma = -10°$ and cutting speeds above 200 m/min, the chips come off as a straight ribbon. At an angle of $\gamma = -20°$ and a cutting speed of 60 m/min, the chips break into segments of 2-4 curls, and at a speed above 75 m/min, they separate as a straight ribbon [1]. The chip colour changes in the same way as with positive leading angles.

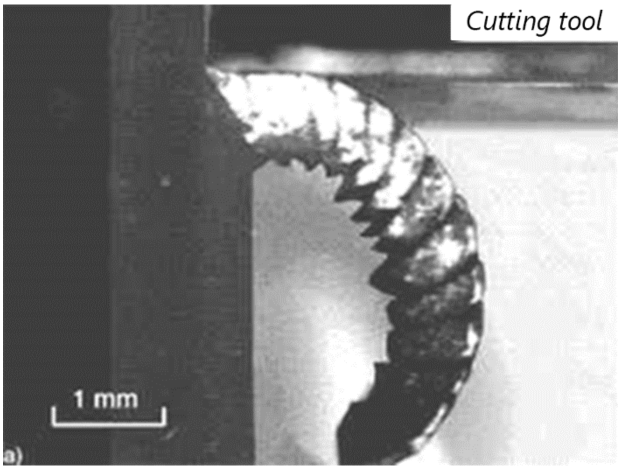

Fig. 1.2.1 Chip formation at a cutting speed of V = 15 m/sec.

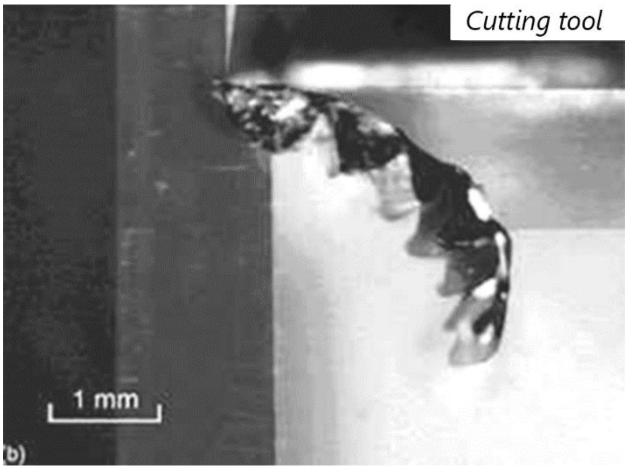

Fig. 1.2.2 Chip formation at a cutting speed of V = 45 m/sec..

Chips produced by a cutter with a negative rake angle of γ = -20° often show significant displacements of individual elements, the outer surface resembling a sawtooth structure, even at a minimum feed rate of s = 0.1 mm/rev. At high cutting speeds, these displacements become less noticeable, and at speeds above 200 m/min, chips produced by cutters with an angle of γ = -20° are visually indistinguishable from those produced by cutters with positive angles. At higher chip thicknesses (greater than 0.1 - 0.3 mm/rev) and at low cutting speeds (40 - 50 m/min), chips produced by tools with negative leading angles are divided into separate elements, forming typical chipping chips. [2]

It can be concluded that the chip compaction tends to increase, especially when working with negative rake angles and cutting speeds up to 40 m/min. However, when the cutting speed is increased above 40 m/min, a decrease in chip compaction is observed, especially when using cutters with negative angles.

Considerable attention is paid to the study of the effect of cutting speed on the change in tangential forces when using cutters with positive and negative rake angles. Studies conducted by American scientists who analysed the tangential forces when cutting steel with cutters with different rake angles in a wide range of cutting speeds (from 30 to 350 m/min) found that at high cutting speeds, the tangential force increases with positive angles and decreases with negative angles. According to the results of the study, at high cutting speeds, the tangential forces at negative angles will be lower than those observed at positive angles. These experiments were carried out on steel 50 and cast iron HB 143 under free cutting conditions with front angles of 20°, 10°, 0°, -10° and -20° and a back angle of 3°, with feeds of s = 0, 1 mm; with cutters with angles of +10° and -10° and a back angle of 3°, with feeds of 0.2 mm; with cutters with angles of +10° and -10° and a back angle of 8°, with feeds of 0.05 mm [3].

The research results allow us to draw the following conclusions about the effect of cutting speed on tangential forces when working with cutters with different front angles:

A. When cutting steels:

1. An increase in cutting speed when using cutters with positive rake angles results in an increase in tangential force.
2. When cutting with zero rake angles in the speed range from 50 to 350 m/min, the tangential force remains stable.
3. Increasing the cutting speed from 50 to 400 m/min when using cutters with negative rake angles results in a decrease in tangential force.
4. The cutting speed at which the tangential forces become equal for cutters with negative and positive rake angles when machining steel 50 reaches approximately 400 m/min.
5. In the speed range from 10 to 40-50 m/min, when using tools with zero and negative rake angles, there is a significant scatter of data with a tendency to increase the forces with increasing cutting speed.

B. When cutting cast iron:

1. When using cutters with both negative and positive rake angles, the tangential forces initially decrease with increasing cutting speed and then stabilise.
2. At low cutting speeds, the tangential forces for cutters with negative rake angles are higher than those for cutters with positive rake angles.
3. At sufficiently high cutting speeds (over 100 m/min), the cutting forces for tools with a negative rake angle ($\gamma = -10°$) are lower than those for tools with a positive rake angle ($\gamma = +10°$).

These findings confirm that high-speed cutting can significantly improve productivity and surface finish. New tool materials and technologies can significantly increase cutting speeds, which in turn contributes to the efficiency of production processes.

1.3 Additive Manufacturing Overview

Additive Manufacturing is a transformative technology that builds objects layer by layer directly from digital models, in contrast to traditional subtractive manufacturing processes where material is removed from a solid block to form the desired part. AM offers unique advantages such as the ability to produce complex geometries, reduce material waste and enable rapid prototyping and low-volume production. Its relevance to the manufacture of centrifugal pump casings lies in its ability to produce intricate internal structures [4][5].

Beyond that, AM has had a significant impact on several industries, demonstrating its versatility and economic benefits.

In the aerospace industry, AM is being used to produce lightweight, complex components that improve fuel efficiency and reduce waste. For example, GE Aviation is using AM to produce fuel nozzles that are lighter and more durable than traditionally manufactured parts [6]. They are also producing 3D printed turbine blades for the GE9X engine that have received FAA certification [7]. NASA's use of metal 3D printing for rocket engine fuel pumps demonstrates a significant reduction in parts and manufacturing complexity [8].

In the automotive sector, AM supports mass customisation and rapid production of complex parts, reducing lead times and increasing production flexibility. Major manufacturers such as GM and Ford have integrated AM for both prototyping and end-use parts to achieve lightweight designs and efficient production. Porsche has successfully tested 3D-printed pistons in its 911 GT2 RS engine, with performance exceeding that of conventional parts [9]. Similarly, Bugatti has developed a 3D-printed brake caliper using aerospace-grade materials, highlighting AM's ability to produce high-strength automotive components [10].

In the energy sector, particularly oil and gas, AM is used to produce durable parts with complex geometries that can withstand harsh environments. This capability, combined with the advantage of producing parts on demand close to the point of use, offers significant logistical and economic benefits [11].

These examples highlight the wider applicability of AM technologies such as SLM, fused deposition modelling (FDM), electron beam melting (EBM) and stereolithography (SLA). In particular, SLM is a key technology for metal parts, using a high-powered laser to selectively melt metal powder particles layer by layer to form dense, high-strength components suitable for demanding industrial applications. Materials such as stainless steel, titanium and aluminium alloys, are commonly used in SLM due to their excellent mechanical properties and corrosion resistance [12].

The design flexibility of AM enables the creation of complex geometries that are difficult or impossible to achieve with traditional manufacturing processes. This flexibility is particularly beneficial for optimising the design of centrifugal pump casings, where internal flow paths can be precisely engineered to improve efficiency and performance. However, AM also presents challenges, particularly in terms of material properties and the need for post-processing to achieve the desired surface finish and dimensional accuracy [4][5].

Post-processing steps such as support removal, heat treatments, surface finishing, debinding and sintering are essential to improve mechanical properties and meet the strict requirements for strength, durability and corrosion resistance of the manufactured parts. While these additional steps can increase production time and cost, the ability to balance the design freedom of AM with the post-processing requirements is critical to achieving cost-effective and high-quality production results [4].

1.4 Circular Economy Considerations

The Circular Economy is an economic model that focuses on eliminating waste and pollution, extending the life of products and materials, and regenerating natural systems. This model contrasts with the take-make-dispose approach of the linear economy, which often results in significant waste and environmental degradation. In manufacturing, the adoption of CE principles can significantly reduce waste, conserve resources and minimise carbon footprints, thereby creating economic opportunities through innovation and efficiency improvements [12].

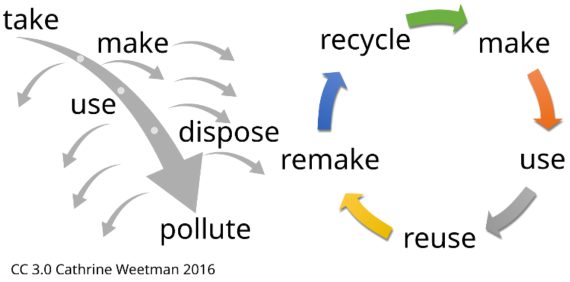

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Figure 1.4.1 Difference between linear economy and the circular economy approach

AM is closely aligned with the principles of CE due to its inherent efficiency and precision. Unlike traditional manufacturing methods, which are often subtractive and generate significant waste, AM processes build parts using only the material required, minimising waste. This efficiency is particularly beneficial in sectors such as aerospace and automotive, where reducing material costs and achieving complex component geometries are critical [13]. In addition, AM's ability to utilise recycled feedstock enhances its compatibility with CE principles, enabling resource conservation and a reduction in the environmental impact associated with material production.

In addition, AM helps reduce CO2 emissions by optimising material usage and enabling lightweight designs that improve fuel efficiency. An example of this is the production of aluminium cylinder heads for garden tools using the EOS M 300-4 1kW laser powder bed fusion 3D printer, which achieved a CO2 reduction of 249.5 kg per part at a price per part comparable to traditional die-casting methods (see Figure 1.4.2). This demonstrates how AM can directly contribute to lower emissions while maintaining economic viability.

AMEXCI

Cylinder Head Job

Air-cooled cylinder head for gardening tools

Conventionally Aluminum Die-Casting Part

For pro version lightweight &
performance optimization is of high importance

CO_{2e} reduction of 249.5 kg

System: EOS M 300-4 1kW
Material: EOS Aluminum AlSi10Mg
Build Time: 1 h per part (36 parts -> 36 h)
Target price for quantities up to 30 000 parts/a
comparable to Die-Cast
Process: Advanced exposure parameters

Figure 1.4.2, Cylinder Heads printed on EOS M300-4 1KW

In the automotive industry, companies such as BMW and Audi have successfully integrated AM and CE by using recycled metal powders in production and optimising part designs to minimise waste. These practices reduce reliance on virgin materials and support a closed-loop production system where end-of-life components are reused or recycled into new products [14]. Similarly, in the aerospace industry, companies such as Airbus are using AM to create lightweight components that improve fuel efficiency while meeting CE principles. The ability to recycle and reuse metal powders in AM processes supports a more sustainable approach to manufacturing, in line with industry goals to reduce carbon emissions and material waste [14].

Material selection remains a fundamental aspect of implementing CE in manufacturing. Metals such as aluminium and steel, commonly used in centrifugal pump casings, are highly recyclable, ensuring that the value embedded in products can be recovered and returned to the production cycle. This reduces the need for virgin materials and lowers the environmental impact of manufacturing processes [15].

By focusing on these strategies and leveraging the capabilities of AM, industries can effectively transition to a circular economy model, reducing their environmental impact while increasing their economic resilience. The incorporation of advanced manufacturing technologies such as AM, along with thoughtful design and material choices, enables the development of more sustainable, efficient and cost-effective production processes, contributing to a more sustainable industrial ecosystem.

2. TECHNOLOGICAL IMPLEMENTATION AND PROCESSES

2.1 Introduction to High-Speed Machining

High-speed machining (HSM) is now considered not only an advanced technology that reduces production time and improves part accuracy, but also an effective strategy for increasing productivity. The use of HSM has a direct impact on reducing cycle times and costs in production, resulting in high quality finished parts and, consequently, increased overall productivity.

Despite progress in reducing metal costs through precision casting, powder metallurgy, and composites, there are still industries that use difficult-to-machine materials that require traditional pressure treatment and machining. In these sectors, specialised equipment is often used, characterised by massiveness, high rigidity and power of the main and actuator drives. Reduced precision requirements are compensated for by additional locking mechanisms.

Among power cutting lathes, machines with inclined guideways (horizontal axis of rotation) and vertical axis of rotation (drawing machines) are used. The inclined bed allows gravity to be used to create a front load, which is useful for intermittent and plunge applications.

Simply increasing the depth of cut and feed rate has its limits, which have already been reached. The limit to increasing the cutting speed is determined by the amount of heat generated during cutting. Attempts to use alternative energy sources, such as ultrasonic vibrations or inductor or laser heating of the cutting zone, have not yielded significant results due to the high cost and complexity of the equipment.

The cutting speed is different from the rotational speed of the object. While high rotational speeds are important for HSM, it is important to keep in mind that the increase in cutting speed is dependent on the diameter of the rotation. The latest developments in high-speed spindle assemblies with hydrodynamic supports (up to 40,000 rpm) have significantly increased machine performance, especially in areas such as precision engineering and instrumentation [16].

The theory of HSM focuses on two main factors: the energy and conditions of metal particle separation and adhesion in the chip formation zone. These aspects are crucial, especially when cutting structural steels at speeds in excess of 700-1000 m/min (with a diameter of 100 mm, the speed varies from 2000 to 3000 rpm). The cutting conditions that achieve these values are usually recommended by tool manufacturers, including not only speed, but also feed rate, depth of cut and coolant usage. These recommendations are based on statistical data on tool life under specific conditions.

The economic justification for using high speeds is particularly relevant for finishing with minimal tolerances. At cutting speeds above 1000 m/min, a qualitative change in the processes of metal tear-off and chip formation occurs. In particular, there is a redistribution of temperatures at the point of contact between the workpiece and the cutting edge, which contributes to greater chip heating, and the high rate of chip displacement relative to the cutter shifts the point of maximum heating from the top of the cutter to its body, thereby improving heat dissipation. The build-up on the cutting edge becomes resistant when using carbide grades or is eliminated when using cubic boron nitride or diamond tools.

Wear-resistant taps with a high hardness of the ceramic base and a sharp cutting edge demonstrate high technical and economic performance. High-speed finishing makes it possible to achieve a surface roughness of Ra 0.40-0.20 and an accuracy of class 5-7, which in some cases eliminates the need for grinding. This becomes especially important in industries where the absence of foreign inclusions is critical, such as in production for the electric vacuum industry.

Interesting results are shown by the use of pulsed laser processing, which, in addition to improving cutting conditions, strengthens the surface of carbon steels at the micro level, which is an additional advantage to the technical advantages of high-speed machining [17].

HSM is defined as not only an innovative technology that significantly reduces production cycle times, but also a strategy that increases productivity and surface quality to the level of post-grinding. This technique allows machining with a 50% or more reduction in time, and ensures high productivity and quality due to maximum spindle speed and feed rate.

However, the practical implementation of these high modes is often more related to scientific research in the laboratory than to everyday practice. The challenges associated with dynamic balancing require innovations in mounting and positioning methods, which delays their widespread use. HSM applications are proving to be effective in industries that require high precision and quality of machining, including aerospace, die making, miniature manufacturing and the medical industry.

HSM technology is particularly useful for complex machining of parts from a single machine, which helps to reduce production time and increase product accuracy. The technology also allows for the machining of not only soft metals such as aluminium, but also hard-to-machine materials, including hardened steel. Given these advantages, HSM is becoming a key technology for industries that require high productivity combined with excellent finish quality.

2.2 Technical Requirements for Equipment in HSM and AM

HSM places high demands on machine design to ensure optimum conditions for precision machining. These requirements include high structural rigidity, effective vibration reduction and damping properties, which are often achieved through the heavy weight of the machine's basic components. In addition, the guides must ensure smooth and precise movement of the moving parts without any play.

Particular attention is paid to the thermal stability of all machine components, as thermal deformations can have a significant impact on machining quality. Modern high-speed machines are equipped with cooling systems that maintain the optimum temperature of the spindle, running screws and other critical elements through the circulation of coolant.

Another important aspect is the materials used to make the basic elements of the machine. For example, the use of natural granite or special mineral ceramics can significantly reduce the susceptibility to thermal deformation, while increasing vibration resistance and structural strength.

In the milling sector, it is important for HSM to have machines with high spindle speeds (up to 20,000 rpm and above) and high feed rates (over 3000 mm/min) to enable efficient machining of complex parts such as moulds and dies. Linear motors in such machines provide rapid acceleration and deceleration of the feed, playing a key role in increasing productivity and machining accuracy.

Thanks to high-speed machining, tasks requiring high precision and surface quality can be realised, making HSM indispensable in modern production in industries where high quality end products are required.

CNC systems in high-speed machine tools play a key role in ensuring machining accuracy and efficiency. They perform important functions that are essential for precise control of tool movement and the workpiece:

1. Look-Ahead preview of the control programme frames: This function allows the system to predict future actions, which ensures smooth programme execution without delays, especially on complex trajectories with sudden changes in direction.
2. Conversion for 5-axis machining: This is necessary to ensure accurate interpretation of programs that control machining on machines with 5 or more axes, allowing for complex cutting operations.
3. Feed rate control: Controlling the feed rate ensures maximum machining accuracy and reduces the mechanical impact on the tool during cutting.
4. HPCC (High Precision Contour Control): HPCC is used to optimise the system's response to changes in the geometry of the workpiece, which improves surface finish and reduces tool wear.
5. Automated path smoothing functions: NURBS (Non-uniform rational B-spline) interpolation enables the CNC to execute smooth and accurate paths that minimise abrupt transitions and impact on the part and tool.
6. High data transfer rate: Essential for executing complex machining programmes without delays, especially in environments where high cutting speeds require rapid updates of CNC instructions.
7. Compensation of errors caused by mechanics: Automatic correction of errors caused by imperfections in the machine's mechanical system ensures higher product accuracy.

These features and functions are an integral part of high-speed machining, where every parameter and function is critical to achieving optimum productivity and accuracy. The HSM CNC must be able to quickly analyse and adapt to changes in the machining process, ensuring high quality of the final product.

For AM, SLM is an effective method for creating parts with complex geometries and high precision, which is important for components such as pump housings. The dimensions of the part (211.65 x 205.73 x 130.29 mm) dictate certain technical requirements that need to be taken into account when choosing a production technology. SLM is particularly cost-effective for small and medium-sized production volumes, where traditional methods such as casting become too costly due to the high cost of tools and moulds. The use of this technology allows for better repeatability, shorter production lead times and the ability to adapt the process to rapid design changes or product upgrades.

In the SLM process, it is important to select the right parameters, such as laser power, layer thickness and scanning speed, to ensure optimal conditions for powder melting and to avoid defects such as pores and cracks. These parameters are selected depending on the surface quality requirements and mechanical properties of the finished part. In addition, an inert gas environment, such as argon or nitrogen, is used to prevent oxidation of metal powders during melting. The use of inert gases ensures process stability and maintains high mechanical properties of the part, minimising the risk of oxide inclusions that can affect the strength and durability of the components.

Modern SLM systems are equipped with sensors for real-time process monitoring, which allows potential defects, such as overheating or uneven energy distribution, to be detected at an early stage and parameters to be adjusted promptly to ensure high quality of the final product. After printing is complete, the parts are heat treated to relieve residual stresses and improve mechanical properties such as hardness and strength, which is particularly important for reliable operation of the pumps in various operating conditions.

2.3 Key Parameters of a High-Speed Spindle

High-speed spindles are fundamental components of HSM machines, which integrate CNC systems, tools and other process elements to make the most of their rotational speed. However, the most important limiting factor in these systems is the bearings, whose durability is critical to ensuring the spindles' stability. Modern designs such as duplex spindles, where two shafts can rotate independently, enable high speeds of up to 10,000 rpm for power applications and up to 30,000 rpm for finishing applications.

Examples of different types of spindles:

- Power spindle: Typically has a speed of up to 15,000 rpm, an ISO 50 taper, power up to 45 kW, and delivers a maximum torque of 400 Nm at 1000 rpm, enabling machining with high material removal.
- Medium spindle: Speeds up to 24,000 rpm, ISO 40 taper, 20 kW power, with 75 Nm of

torque at 3,000 rpm, used for less torque-demanding applications.

- High-speed spindle: For very high speeds of up to 40,000 rpm, ISO 30 taper, 12 kW power, 48 Nm torque at 30,000 rpm, ideal for finishing applications with high precision.

Such spindles require specialised bearings such as ball, hydrostatic, aerostatic or electrostatic bearings, depending on the maximum speed. High speeds require that all components are optimised to the maximum extent possible to ensure accuracy, wear resistance and minimal heat.

The main requirement for high-speed spindles is to maintain high accuracy and minimal thermal deformation during operation, as any thermal changes can affect the quality of the final product. This is achieved through the use of a specialised cooling system and high-quality construction materials [18].

Let's look at the example of high-speed spindles from the Swiss company IBAG, a set of technical solutions implemented by IBAG to ensure the quality and reliability of high-speed motor spindles.

1. Options for position, temperature and vibration monitoring.

A high degree of process reliability is ensured by so-called Condition Monitoring - extensive monitoring and control. For this purpose, sensors that are carefully designed and as close to the process as possible are essential. That's why IBAG Switzerland AG supplies its HF motor spindles with a variety of sensors and actuators as an option.

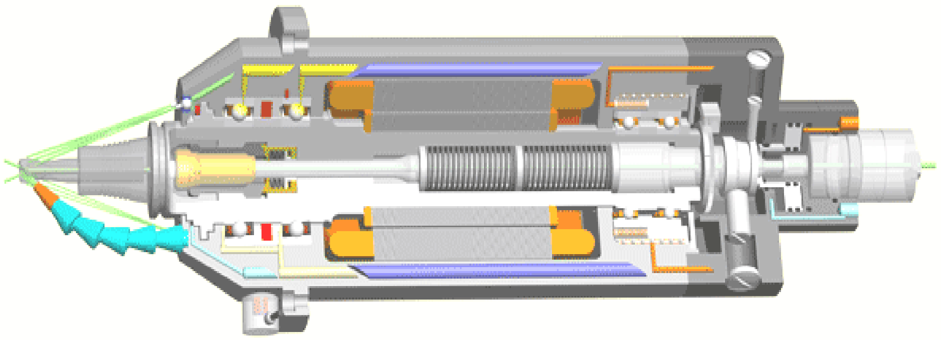


Figure 2.3.1 Condition Monitoring equipment: HF motorised spindle with proven sensors and actuators for monitoring and reliability of high-speed machining.

2. Option M of IBAG's high-speed spindles includes a displacement sensor that measures mechanical or thermal displacement of the shaft to within micrometres. This information can be used by the CNC system to compensate for any misalignment, which significantly increases machining accuracy, especially in critical operations such as finishing drilling.

The M+ option includes additional temperature sensors on the spindle housing and outer bearing ring. The PT100 and PT1000 sensors are capable of sending signals about the current temperature status, enabling the CNC to adapt to the operating conditions by stopping machining or adjusting cutting parameters to reduce temperature and prevent overheating. This is critical for continuous operation in automated and unmanned environments, where temperature management can prevent costly stoppages and equipment damage.

The M and M+ options are therefore essential for maintaining high precision and reliability in high-speed machining by monitoring and adapting the spindle's operating conditions to the current state and machining parameters.

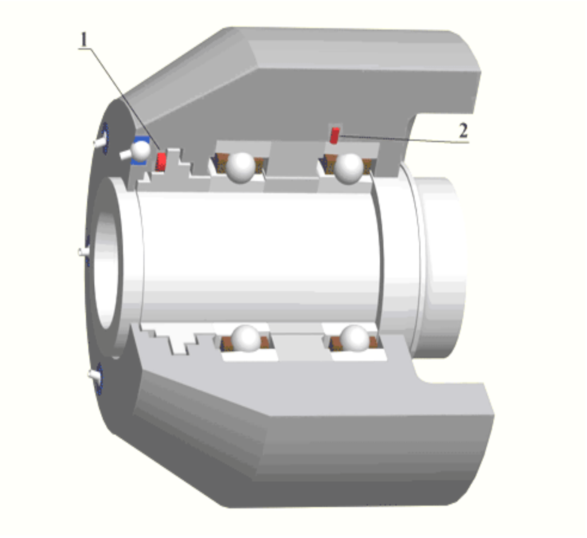


Figure 2.3.2 Order of accuracy - μ units are provided by sensor 1 for measuring axial misalignment of the spindle shaft; 2 - temperature measurement sensor.

3. Vibration sensors are a key part of IBAG's condition monitoring system for high-speed spindles. They help to detect and diagnose various problems related to tool balancing, machining parameters or potential malfunctions. The sensors are able to measure and compare vibration levels with pre-set limit values and send three types of messages: green (normal), orange (warning) and red (error). This allows for quick response to any problems, minimising risks to the equipment and optimising the maintenance process.

Additionally, monitoring the toolholding system is critical in ensuring reliable and accurate machining. The toolholding system is equipped with sensors that check the presence and correctness of the tool clamping, which helps to avoid errors during automatic tool changes. The digital and analogue sensors can be integrated with a variety of CNC and PLC systems for maximum compatibility and flexibility in setup.

IBAG motor technology also features advanced solutions for high performance and efficiency. Alternating current is used to provide power at medium to high speeds, while direct current is used to maximise torque at low speeds and minimise the thermal impact of the motor on the spindle shaft. This enables IBAG spindles to be used for a wide variety of machining tasks, including high-precision and finish milling.

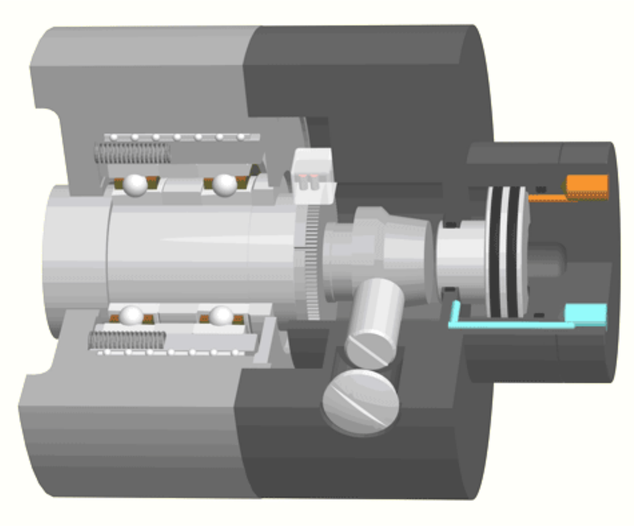


Figure 2.3.3 A special sensor ensures reliable automatic tool change.

4. The rigidity and precision of IBAG spindles over a wide range of speeds are ensured by various bearing configurations, which allows them to be optimised for specific production requirements:

1. The tandem (TD) configuration is the standard option for small and medium-sized spindles. It is suitable for applications where high rotational speeds are required.
2. ‘O’ configuration - provides greater spindle stiffness in both axial directions and less dynamic displacement. This configuration reduces the maximum rotational speeds, but is suitable for applications where stability is required, such as drilling.
3. OTD configuration - typically used for heavy spindles and applications where high

torques are required to remove large amounts of material with long tools.

Lubrication systems:

- Oil mist lubrication - This system allows the precise calculation of the amount of air-oil mixture to be fed directly to the hybrid ceramic bearings. This minimises wear and increases lubrication efficiency.
- AI-lubrication - the supply of minimal oil through small holes in the outer ring of the bearing optimises lubrication and reduces bearing temperatures.

The spindles are protected from external contamination by the use of a suspension cable, which also helps to avoid unnecessary contamination of important components.

IBAG's holistic approach to spindle development and implementation enables high performance and precision in a wide range of machining operations, from heavy material removal to precision drilling and milling.

5. The innovative variable bearing preload system in spindles is key to ensuring their durability and high performance at different rotational speeds. High-speed spindles often use a hydraulic system to automatically adjust the preload of the ceramic ball bearings to adapt to changing operating conditions:

1. Low rotational speeds - High preload is required to ensure high rigidity and stability, which is critical when using large tools.
2. High rotational speeds - Lower preloads are more suitable for small tools, minimising heat generation and bearing wear, and increasing rotational dynamics.

The variable preload system also helps to dampen vibrations associated with spindle speed. This improves surface finish and ensures more efficient use of spindle power, ultimately resulting in lower production costs and higher overall productivity.

6. IBAG offers a variety of coolant systems that optimise the cooling of tools and workpieces, which are critical to maintaining high quality machining at high speeds:

1. Coolant supply TCW1:
    - Four to six adjustable nozzles are mounted on the front of the spindle housing.
    - The coolant flows through a special coupling at the rear of the spindle, passing

through the housing to the cutting area.

   - This solution is ideal for tool cooling and chip evacuation, as well as for blowing air over the workpiece.

2. Optional coolant supply TCW2:
   - Flexible nozzle on the spindle head.
   - Typically used for additional coolant supply, such as air or oil, especially during drilling and threading operations.
   - Suitable for almost all medium and large spindles.

3. Pressurised coolant supply through the centre of the spindle (option W):
   - Cools and flushes chips directly in the area of the tool's cutting edges.
   - Prevents chip burr formation and cutting edge breakage, improving surface finish.
   - It is essential for drilling deep holes and milling grooves and pockets.
   - It is suitable for use at pressures up to 80 bar and rotational speeds up to 30,000 rpm.

These options provide flexibility in the choice of cooling methods, allowing the production process to be tailored to the specific needs of the material and type of processing, thereby increasing production efficiency.

Selecting the optimum machining parameters is one of the most challenging tasks in practical HSM applications, as each new tool and workpiece combination requires numerous tests. The ideal choice, which ensures minimum machining time with high accuracy, depends on the right combination of machining parameters, tool, workpiece material and part shape. Results often deviate from the desired optimum.

IBAG offers specially developed P-Calc software to address these challenges. It is based on an extensive database that includes information on workpiece materials, tools and HSM spindle parameters. The calculation process is as follows:

- Selecting a material from the P-Calc database that contains the required characteristics.
- Selecting a tool from the database, which contains the permissible and optimal cutting parameters.
- Setting the geometry of the machined surface.

Based on the information entered, the system calculates the required spindle power and torques as well as the radial and axial forces acting on the tool. The system then determines the optimum cutting parameters and plans the process that is best suited to the application.

P-Calc avoids the selection of unacceptable cutting conditions, reducing the risk of overloading and spindle breakage.

HSM spindles from IBAG Switzerland AG are widely used in the automotive and aviation industries worldwide. Among IBAG's customers are several well-known brands:

- BMW, Germany, where IBAG spindles are used in machining centres to produce aluminium rear axles for the 5 Series Limousine.
- PSA (Peugeot), France, where IBAG spindles are used to manufacture aluminium engine blocks on unique TRICEPT machines that process six spindles simultaneously.
- Delphi Automotive, USA, where IBAG spindles are used to manufacture mechanical and electrical components for automobiles

In the aviation industry:

- Pratt & Whitney and Lockheed use IBAG spindles to machine parts for turbines and other components.
- NASA uses IBAG spindles in the manufacture of aerospace vehicles.
- Boeing in the United States and Airbus A380 in Europe also use IBAG spindles at Ingersol machining centres to produce aluminium parts, including the spars and body stringers of the Airbus A380. The spindles, which reach speeds of up to 60,000 rpm and high power, provide high cutting and feed rates that minimise machining time and enable cost-effective production of complex, large-sized parts in solid metal.

IBAG Switzerland AG's spindles for HSM are known for their power outputs of up to 195 kW and rotational speeds of up to 100,000 rpm. They are equipped with ceramic hybrid bearings arranged in ‘O’ or ‘tandem’ configurations and are complemented by temperature and vibration sensors to monitor performance. Active bearing preloading and high quality damping ensure precision and quality machining. The coolant flow through the centre of the spindle effectively removes chips, particularly when machining aluminium, ensuring process reliability.

HSM is critical for machining accuracy and shortening production cycles. Effective use of spindles in HSM is not possible without the right software, such as Autodesk, which provides process optimisation and is widely recognised in Ukraine.

2.4 Cutting Tool for HSM Optimisation

Cutting tools for HSM have to meet high standards of durability. Leading manufacturers offer a wide range of cutters for HSM applications, accompanied by detailed recommendations for applications and cutting conditions. The latest fine grades are being developed to ensure reliable operation at high speeds. The tools are made from materials such as micrograin carbides, polycrystalline diamonds, cubic boron nitride, titanium carbide and others, often with wear-resistant coatings to increase machining speed and tool life.

It is also important to choose toolholding systems that maintain precise cutter positioning and minimise vibrations. Due to the reduced cutting forces during HSM, precise tool balancing is crucial, requiring the use of specialised chucks with balance adjustment or balanced thermal clamps.

HSM shanks are often used for high-speed machine tools, which feature a shortened hollow taper and a special fixation pattern that provides increased precision. HSK shanks have a significantly lower static yield than conventional 7:24 taper shanks, which improves stability during cutting by a factor of 6-7.

Figure 2.4.1 Graphite electrode after HSM, size 350 × 200 mm; 9600 hexagonal holes with a radius of 0.2 mm; outer surface treatment with a 10 mm ball mill; hole treatment with a 1.5 mm roughing mill; finishing with a 0.4 mm mill; spindle speed 45,000 min-1, processing time 34 hours.

Effective use of HSM requires a harmonious combination of high-quality equipment and advanced control programme development. This results in significant reductions in machining times not only due to the sheer speed of the machining, but also by minimising manual finishing. HSM also enables efficient machining of heat-treated tool steel and other difficult-to-machine materials.

An important aspect is justifying the investment in high-speed equipment. Although HSM machines cost about twice as much as conventional machines of similar size, their operating costs remain roughly the same, except for the cost of cutting tools. For example, the cost of HSM tools for machining graphite and copper electrodes is 4-5 times higher, and for tool steels, 10-12 times higher than for conventional machining. However, the high costs are partially offset by the long tool life and reduced depth of cut.

Therefore, it is important to carefully calculate the cost-effectiveness of introducing high-speed technologies in production, taking into account the increased cost of equipment and tools, but also the potential time savings and improved processing quality.

2.5 Additive Manufacturing Processes

For the casing in question, Selective Laser Melting (SLM) method was selected as it is an advanced additive manufacturing technique used primarily for creating complex metal parts with high precision. This process is particularly well-suited for producing intricate geometries, such as those found in centrifugal pump casing under review.

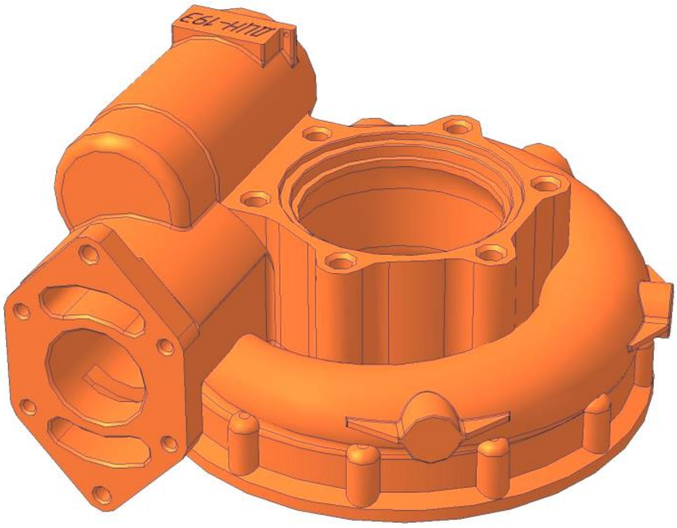


Figure 2.5.1 Centrifugal pump casing

This casing is originally made from aluminum alloy AlSi7Mg, which is also available as F357 powder for SLM process. It was selected for its main characteristics:

- Light-weight
- High corrosion resistance
- High dynamic load bearing capacity

And typical applications:

- Aerospace industry applications
- Defense and automotive industries
- Structural components requiring high strength

Table 2.5.1 Powder chemical composition (wt.-%) [19]

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	Other elements, each	Other elements, total
Min	Balance	6.5	-	-	-	0.40	-	0.04	-	-	-
Max		7.5	0.10	0.20	0.10	0.7	0.10	0.20	0.002	0.05	0.15

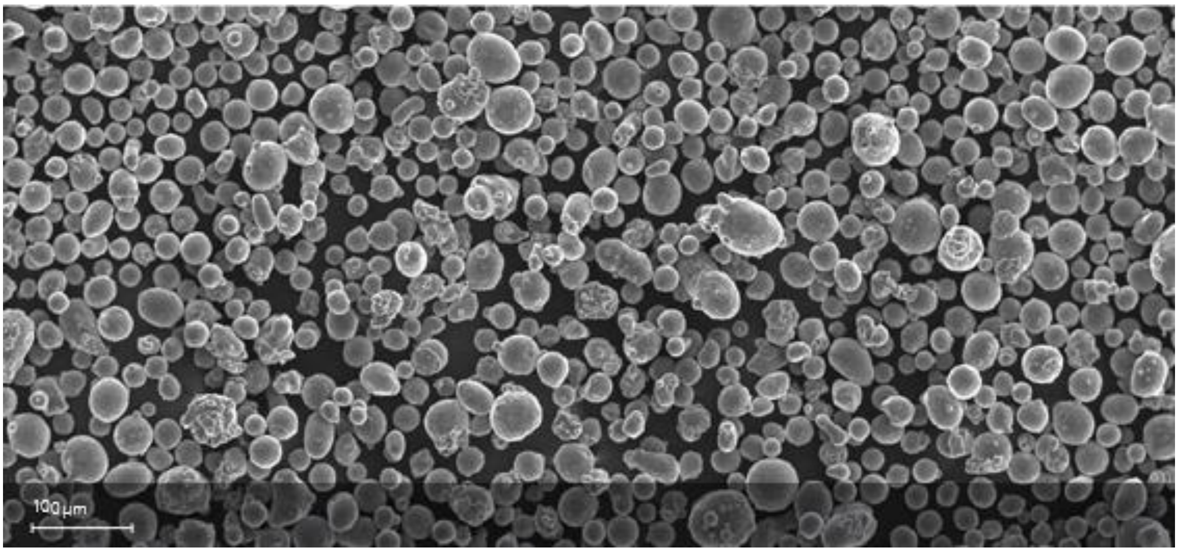


Figure 2.5.2 SEM Image of EOS Aluminum ALF357 Powder. [19]

Table 2.5.2 Generic particle size distribution

D10/um	D50/um	D90/um
15	30	50
25	40	60

The process begins with a thin layer of powder spread uniformly over the build platform.

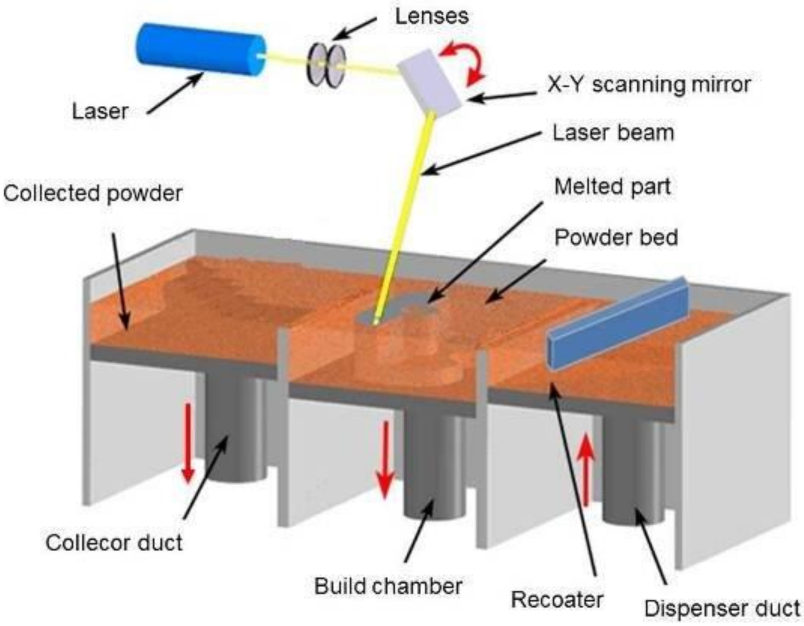


Figure 2.5.3 The schematic diagram of the SLM process.

A high-powered laser then selectively melts the powder according to the cross-sectional shape of the part.

As the laser moves over the powder bed, it creates a molten pool that selectively melts the metal powder to form solid layers. Each layer melts and fuses with the previous one to form a structure.

Once printing is complete, the part is allowed to cool gradually in the build chamber to reduce thermal stress. This controlled environment prevents warping or cracking that could result from rapid cooling.

Post-processing is essential to achieve the desired mechanical properties and surface finish required for centrifugal pump casings. Specific post-processing steps include:

- Build plate separation

In order to print a component using SLM, a substrate plate is required as a foundation. This plate, often made of a material compatible with the powder (e.g. aluminum for aluminum powder), provides stability, prevents distortion and conducts heat away from the component and the powder bed. After printing, the part remains attached to the build plate and requires mechanical separation, typically using methods such as wire EDM or a band saw. The build plate is reusable but requires regular maintenance to ensure flatness and optimum surface quality for future prints.

Figure 2.5.4 Example of a part on the build plate with support structures

- Removal of Support structures

Support structures are non-functional parts that are removed after the building process. In powder bed fusion AM, support structures are removed mechanically by applying force or cutting (often manually). In SLM, support structures are required for thermal dissipation, printability and part balance. Wire erosion, saws, Dremel handheld power tools and pliers are all commonly used methods to remove support structures from PBF parts. Sandpaper effectively removes marks left on the bottom by supports [20].

The laser melting process involves extremely rapid melting and resolidification. Due to the layered nature of the process, parts exhibit anisotropic properties depending on the direction of build. Appropriate heat treatments can be used to meet the requirements of different applications, e.g. to reduce the anisotropy.

For our application, critical surfaces, especially sealing areas and mating faces, will need precision CNC machining to meet tight tolerances and achieve a smooth finish. Although threads can technically be printed, this may result in incomplete areas on the thread teeth. Given the high pressure between the two halves of the pump casing, such imperfections are not acceptable, and precision machining would be required to ensure reliable performance and prevent leaks.

After machining, polishing may be applied to further refine the surface finish. In addition, anti-corrosion coatings can be added to increase durability, especially in environments where the pump casing will be exposed to corrosive fluids.

Ensuring the integrity and performance of SLM-printed parts requires stringent quality control measures. Non-destructive Testing (NDT) methods, such as X-ray computed tomography (CT), ultrasonic testing, and dye penetrant inspection, are employed to detect internal or surface defects such as porosity, micro-cracks, and inclusions that could compromise the part's structural integrity. X-ray CT is particularly effective for examining the internal structure of parts printed from aluminum alloys like AlSi7Mg, identifying any porosity that may have formed during the rapid melting and solidification phases.

Dimensional inspection using tools such as coordinate measuring machines (CMMs) or laser scanners ensures that the geometry of the printed part conforms to the design specifications and meets all critical dimensional requirements. Advanced techniques such as Electromagnetic Acoustic Transducers (EMAT) and Eddy Current (EC) testing offer additional capabilities to monitor residual stresses in real time, which is essential for components exposed to high pressures, such as pump housings.

By incorporating these quality control processes, manufacturers can effectively identify and mitigate potential issues, ensuring that SLM-printed components maintain high reliability and performance throughout their operational service life.

2.6 Requirements for CAM Systems

2.6.1 CAM Software for HSM

Modern CAM systems are actively developing to meet the requirements for creating new tool movement strategies [21]. The main criteria that a modern CAM system for HSM must meet include:

- ensuring consistent cutting conditions with a constant chip thickness;
- radial conjugation of sharp corners of the trajectory for optimal cutting conditions;
- smooth joining of paths during positioning;
- a variety of options for smooth tool feed and retraction;

- application of helical and equidistant machining strategies, as well as selection of the optimal strategy for different machining zones
- Automatic smoothing of paths in corners;
- Avoidance of full cutter width passes and automatic implementation of trochoidal plunging;
- optimisation of feeds for uniform tool load.

Autodesk is a leader in the development of CAM systems for HSM and actively cooperates with machine tool manufacturers. The company not only participates in European projects, but also constantly improves HSM technologies by introducing new machining strategies. One of the key tools is a CAM system that can work with a 3D model of the residual allowance. Such a model allows cutting only in those places where material remains, significantly reducing the time for idle passes.

Importantly, CAM systems such as PowerMILL (part of Autodesk Fusion) can automatically update the 3D model of the residual workpiece after each pass. This model is used to plan the next passes on the other side of the part. The user can visually view the final material on the computer screen.

Additionally, the CAM system should include sufficient strategies for machining complex cavities and bottlenecks (Figure 2.6.1.1). Positional machining is used to improve accuracy and reduce time, and continuous five-axis milling is used for complex shapes. If it is not possible to reduce the length of the cutter by changing the angle of inclination, continuous five-axis milling must be used to ensure the required accuracy and quality of the machining.

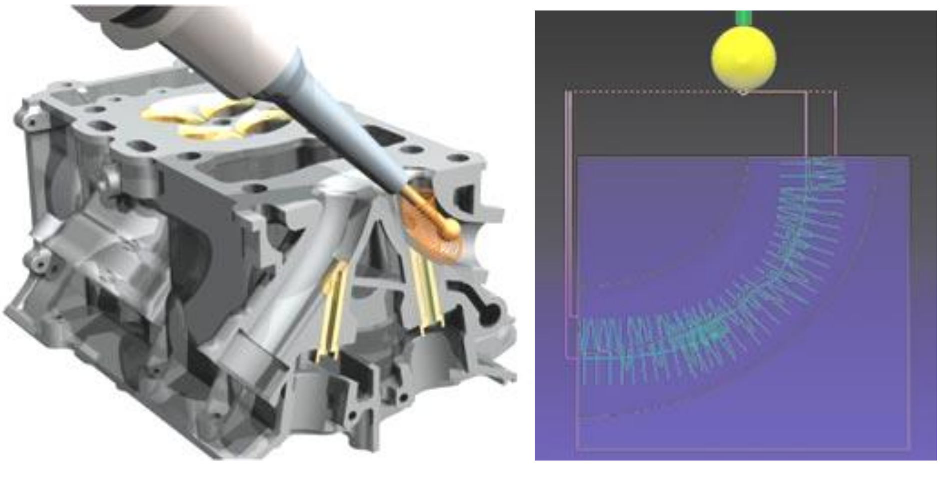
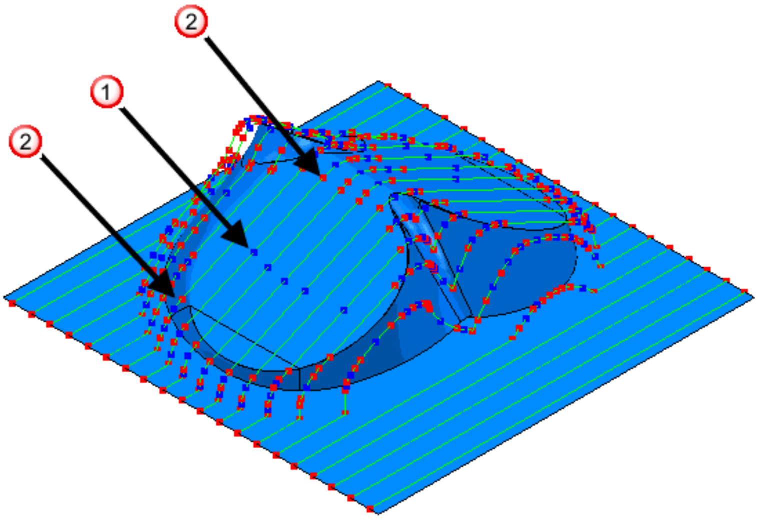


Figure 2.6.1.1 PowerMILL CAM system for channel processing

PowerMILL's Port Machining module is specifically designed for efficient channel machining, automatically distinguishing between areas suitable for 3-axis or 5-axis machining. It provides a choice between helical and plunge strategies and supports all types of tools, including round ball mills. This module also includes specialised strategies for machining complex parts such as turbine blades and impellers, developed in collaboration with leading aircraft engine manufacturers [22]. The process of preparing a programme for such parts takes about 30 minutes using PowerMILL.



① The blue points indicate the arc centres.

② The end points of the arcs are the red points either side of a blue point.

Figure 2.6.1.2 PowerMILL option “Fit arcs”

Modern CNC systems are equipped with algorithms that automatically smooth out broken paths, creating a smooth transition between segments depending on the step length and angle between segments. Using this feature, which allows you to set the traverse according to the parameters of the CNC system, ensures that the movement does not change speed at bends in the path. For example, PowerMILL uses a point redistribution function that optimises the path by removing redundant points within a specified tolerance. To illustrate: on a Huron KX8-Five machine with Siemens 840D control, the use of even point distribution reduced cutting time from 82 to 50 minutes (Figure 2.6.1.3), resulting in a saving of almost 40%.

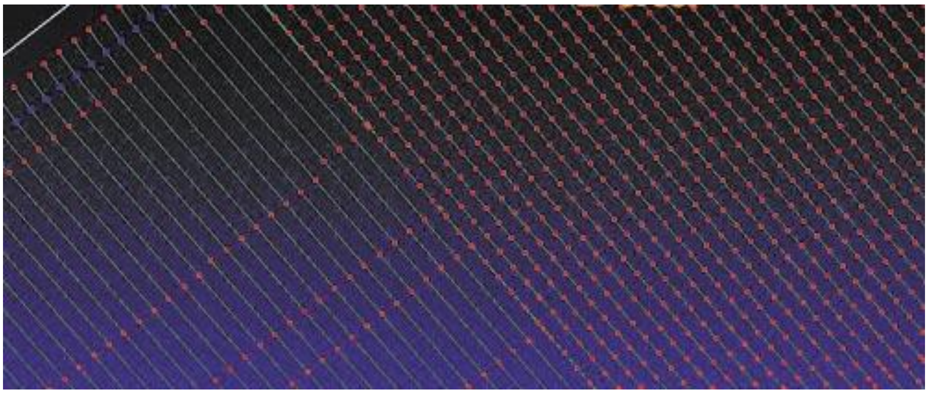


Figure 2.6.1.3 The left side of the figure shows a machining path optimised within tolerance with point redistribution.

The CAM system needs to be able to quickly create small-pitch passes for high feed rates while avoiding sharp turns. A CNC system with look-ahead reduces the speed at change of direction points, which increases accuracy and reduces machining time. This enables milling with minimal or no polishing on the finish.

The CAM system must also effectively address the problem of “data starvation” by optimising toolpaths using G-codes or NURBS technology to ensure cutting stability and minimise machining time [23]. This includes taking into account the distance between the layers along the Z-axis, smoothly connecting the ends of the paths, controlling wall slope, and identifying geometry features.

For example, the CAM system must adapt the layer spacing to bring the machined surface as close as possible to the final shape with the required allowance. Features such as smooth tool insertion or trochoidal machining help reduce tool wear and shorten machining times.

2.6.2 CAM Software for Additive Manufacturing

Additive manufacturing requires specialised CAM software that can effectively manage the complexities of layer-by-layer production and optimise material usage, build orientation and support structures. Two advanced CAM solutions tailored for AM processes are Autodesk Fusion and Autodesk Netfabb. Both offer powerful tools designed to improve the accuracy and efficiency of additive manufacturing, particularly for complex geometries such as centrifugal pump housings.

Autodesk Fusion is a versatile platform that can also be used for various additive manufacturing processes, providing a unified environment for design, engineering and manufacturing. Its additive manufacturing capabilities are particularly beneficial due to:

- Generative design: Fusion 360 uses powerful generative design tools to create optimised structures based on specific design criteria such as strength, weight and material usage.

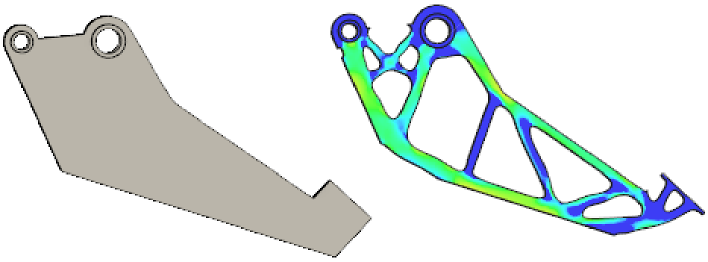


Figure 2.6.2.1 Topology Optimisation

- Simulation capabilities: Fusion's simulation tools allow users to analyse part performance under various operating conditions, including stress, strain and thermal effects. These simulations help predict potential problems before printing, ensuring that final parts meet all required specifications.

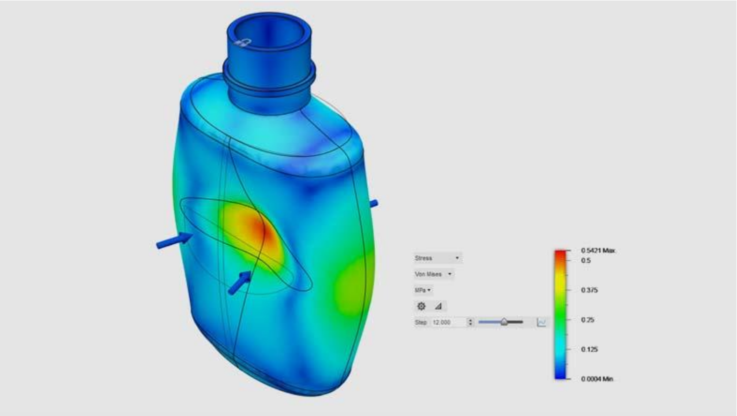


Figure 2.6.2.2 Nonlinear Static Stress Simulation

- Customisable slicing and support generation: The software provides customisable slicing strategies and support generation options, allowing precise control over the build process. This flexibility helps to optimise build orientation and minimise support material, reducing waste and production costs.

But an even more suitable tool would be Autodesk Netfabb, which is designed specifically for additive manufacturing workflows. It offers a comprehensive set of features for preparing, optimising and validating models before printing. Key features of Netfabb include:

- Advanced mesh repair and preparation: Netfabb's mesh repair tools automatically fix common problems during import, such as non-manifold edges, holes and lattice mesh.

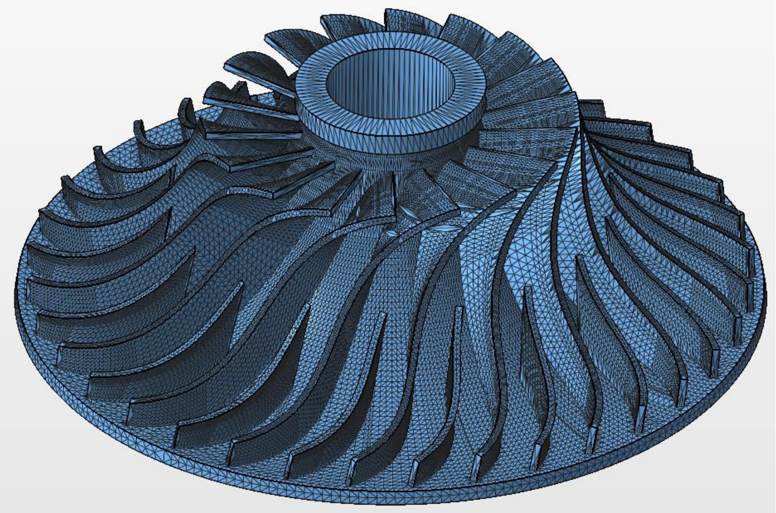
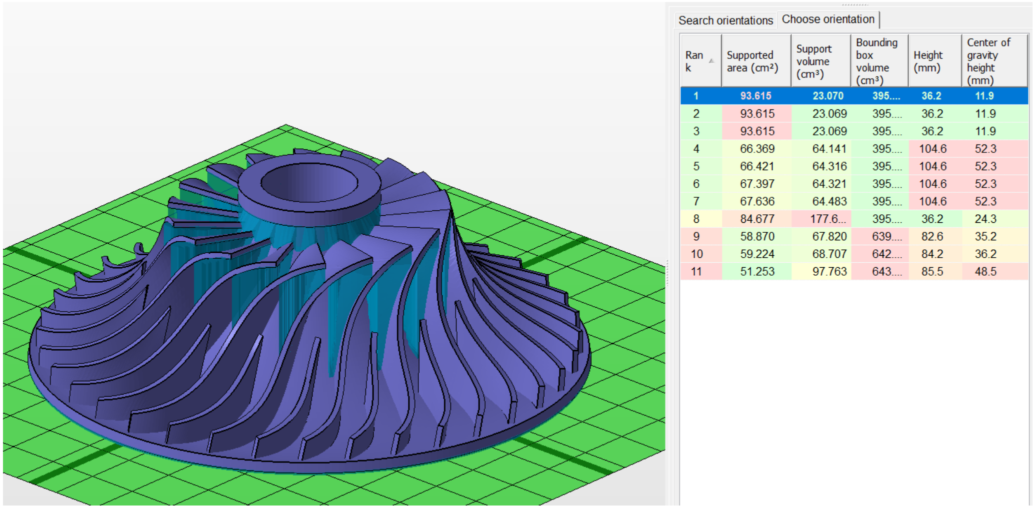


Figure 2.6.2.3 Repaired Mesh example

- Orientation and support structure optimization: The software automatically identifies the best build orientations for the part and provides a list of potential options while generating optimised support structures. It is important to note that due to the layer-by-layer nature of additive manufacturing, the part may have anisotropic properties depending on the build orientation chosen.



Rank	Supported area (cm²)	Support volume (cm³)	Bounding box volume (cm³)	Height (mm)	Center of gravity height (mm)
1	93.615	23.070	395....	36.2	11.9
2	93.615	23.069	395....	36.2	11.9
3	93.615	23.069	395....	36.2	11.9
4	66.369	64.141	395....	104.6	52.3
5	66.421	64.316	395....	104.6	52.3
6	67.397	64.321	395....	104.6	52.3
7	67.636	64.483	395....	104.6	52.3
8	84.677	177.6...	395....	36.2	24.3
9	58.870	67.820	639....	82.6	35.2
10	59.224	68.707	642....	84.2	36.2
11	51.253	97.763	643....	85.5	48.5

Figure 2.6.2.4 Automatic Orientation and Support Structure Generation

- Automatic fill by build volume and packing

There are a number of 3D packing methods, the main ones that could be used are "3D Packing - Scanline", "3D Packing - MonteCarlo" and "3D Packing - Gravity".

MonteCarlo is usually used for packing jobs with a large number of parts or when you are dealing with interlocking. The Gravity method allows the parts to "fall" and settle in the workspace using simulated gravity. Scanline packs parts in the build volume based on their physical shape.

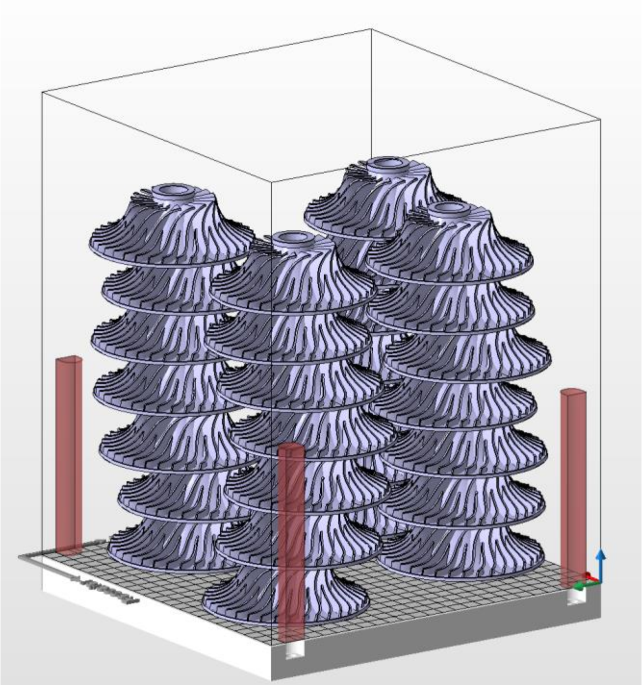


Figure 2.6.2.5 Packing of 28 parts

- Slicing and toolpath control: Netfabb provides control over slicing parameters and toolpath strategies.

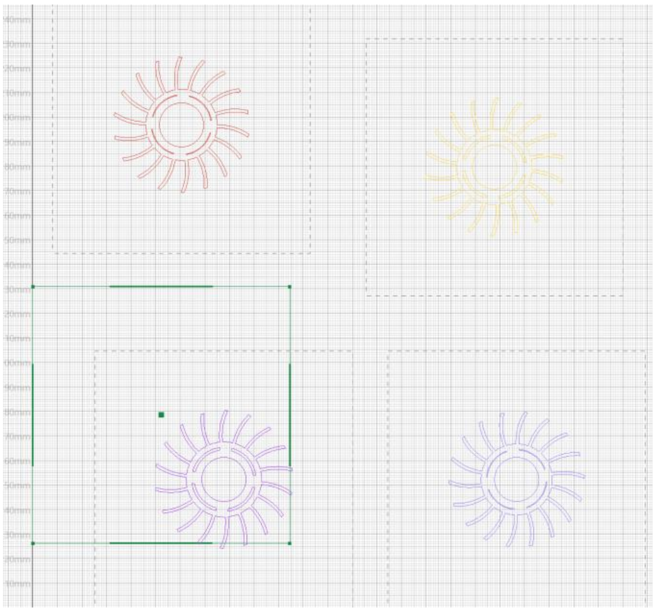


Figure 2.6.2.6 Layer 848/8480

- Build simulation and analysis: Netfabb includes advanced simulation tools that predict potential build failures caused by thermal stress and distortion. This allows users to preemptively adjust parameters to optimise the build process.

Both Autodesk Netfabb and Fusion 360 provide powerful tools for optimising additive manufacturing processes from design through to final production. Their advanced simulation and generative design capabilities help ensure that parts, meet high standards of quality and performance while minimising material waste and production time..

2.7 Tool Path Generation Methods for HSM

Basic principles of creating control programmes for HSM:

1. Long cutting paths: Toolpaths with minimum depth in the axial and radial directions should be favoured, allowing for efficient use of the cutting edge and reducing mechanical stress on the tool.
2. Circular cutting: Instead of face milling, it is recommended to use circular cutting, where the circumferential speed is directly proportional to the tool radius. This reduces cutting forces, especially in the X and Y axes, and promotes better chip evacuation while reducing tool stress.
3. Smooth change of cutting conditions: Ensuring constant cutting conditions, including chip evacuation and cutting forces in the axial and radial directions. For modern carbide tools, a stable, high temperature in the cutting zone is more important than temperature

fluctuations, which can have a negative impact on tool life and machining quality.

4. Smooth toolpaths: Look-ahead and feed rate adjustment features minimise sharp cuts and provide smoother transitions in complex paths, reducing the risk of tool and part damage.

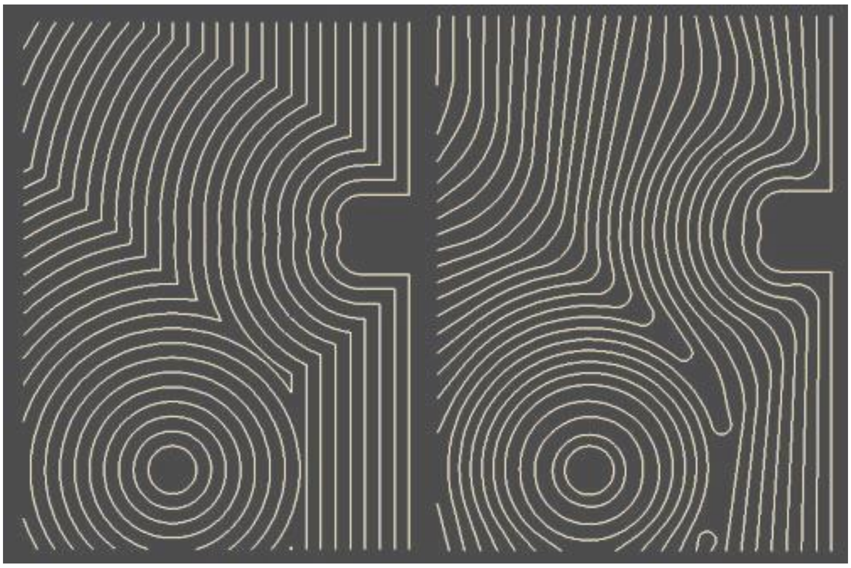


Figure 2.7.1 Example toolpaths for conventional milling (left) and HSM (right)

Parts with complex geometries often require trajectories with abrupt changes in direction, but these situations should be minimised. CAM system developers are trying to create software tools that allow for maximum smoothness of trajectories, which is especially important for HSMs to ensure high quality machining and production efficiency (Figure 2.7.2).

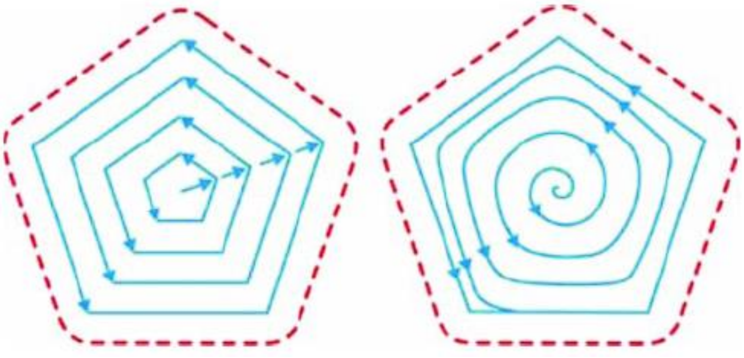


Figure 2.7.2 Trajectory types

When working with high-speed spindles, the cutting force in the Z-axis direction decreases only slightly with increasing rotational speed. Plunging into hard material at high feed rates can cause considerable stress on the toolholder and spindle, often resulting in tool damage. Vertical plunge cutting should be avoided unless working with soft materials such as graphite or aluminium.

To reduce the risk of damage, the cutting tool should be lowered by the amount of the Z-axis stroke in the air and plunged into the material in a horizontal arcuate path. It is also recommended that the tool exit the material in an arc. When machining pockets, CAM functions such as HELIX and RAMP can be used for helical plunging, with the helix angle kept below 2 degrees. The harder the material, the smaller the plunging angle should be; for example, for steel with a hardness of 62-65 HRc, the plunging angle should not exceed 0.5 degrees.

Parallel layer cutting remains a popular method for pre-processing due to its easy programming and consistent milling depth. It is even suitable for older machines with 2-axis CAM systems. The toolpath in this method includes lifting, lowering and two-axis zigzag milling. Although not ideal for HSM due to the uncontrolled contact of the cutter with the workpiece, it is optimal for HSM pre-machining, providing precise control of the depth of cut on each layer.

Modern CAM systems provide control of path joints during the transition between layers and allow for the programming of combined paths for different types of surfaces. Ideal systems automatically distinguish between inclined and horizontal surfaces when combining machining methods in a single programme. In the absence of such functions, the programmer must manually combine the methods. The problem of changing the Z-axis pitch remains important: some CAM systems automatically adapt the pitch depending on the slope of the walls, while others require manual adjustment for optimal surface roughness.

3. PRACTICAL IMPLEMENTATION AND PROCESS OPTIMIZATION

3.1 Characteristics of High-Speed Machining

Milling is one of the key processes in metalworking, taking up to 35% of the total machining time, and sometimes even up to 100%. This emphasises its importance in the production process.

High Speed Machining significantly improves the efficiency, accuracy and quality of machining by using high cutting speeds. This helps to reduce the workpiece material to a softer state and reduce cutting forces, which allows the tool to operate at higher feed rates. The theoretical basis for HSM is based on Solomon curves, which demonstrate a decrease in cutting forces at certain speeds (Figure 3.1.1).

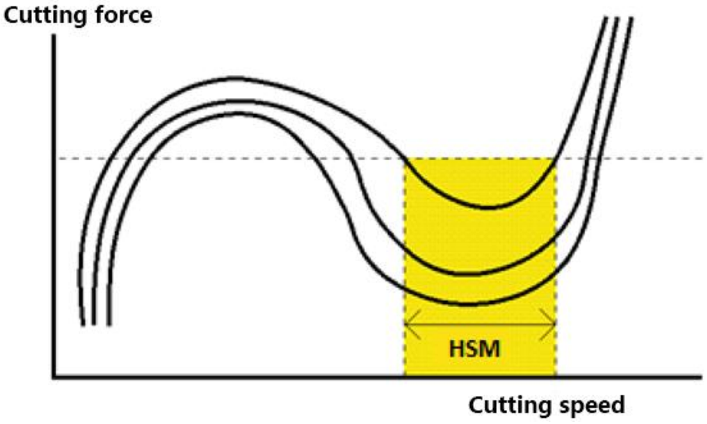


Figure 3.1.1. Solomon curves, cutting forces versus cutting speed

HSM machines are capable of high speeds of up to 40,000 rpm and high feed rates of up to 20 m/min at small depths and widths of cut. This increases the volume of metal removed several times over conventional machining. The contact time of the cutting edge with the workpiece and chips is very short and the chip removal rate is high, so that most of the heat generated during cutting is removed with the chips, leaving the workpiece and tool unheated. In HSM, 80% of the heat generated during chip formation is generated in the area of mechanical deformation of the material, 18% in the area of chip-tool contact, and 2% due to friction of the cutting edge against the material.

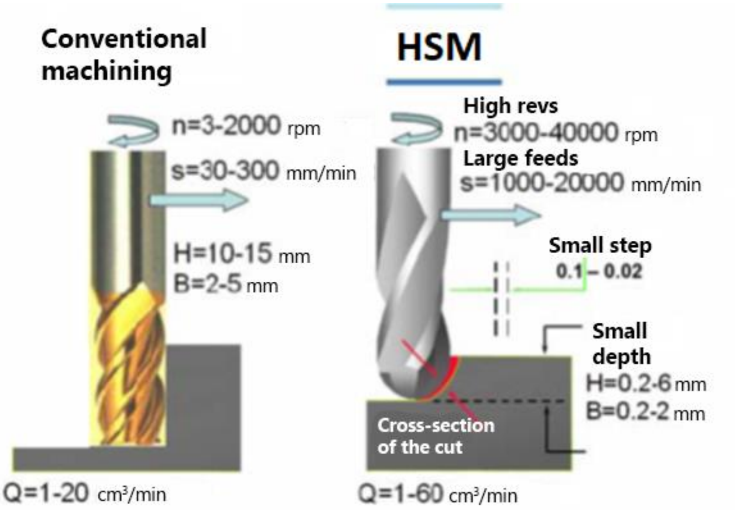


Figure 3.1.2. HSM characteristics compared to conventional machining

Studies conducted during HSM with the right parameters show that 75% of the heat generated is effectively dissipated with the chips, 20% through the tool, and 5% through the workpiece, with chip temperatures in the cutting zone reaching 600 °C. It is also recommended that the depth of cut should not exceed 10% of the cutter diameter, which allows for surface quality comparable to EDM, especially when blade machining hardened steels.

The main advantage of HSM is not so much the reduction of machine time by intensifying cutting modes, but rather the improvement of machining quality and the efficient use of modern CNC machines. Success in high-speed machining depends on the correct choice of all process components: machine tool, CNC system, cutting and auxiliary tools with a clamping system, programming system, as well as the qualifications of the programmer and machine operator. Ignoring any one of these components can negate all previous efforts. Research into HSM has shown its advantages over traditional machining methods. In particular, Solomon's research in 1931 proved that the temperature versus cutting speed relationship for most materials is extreme (Figure 3.1.3).

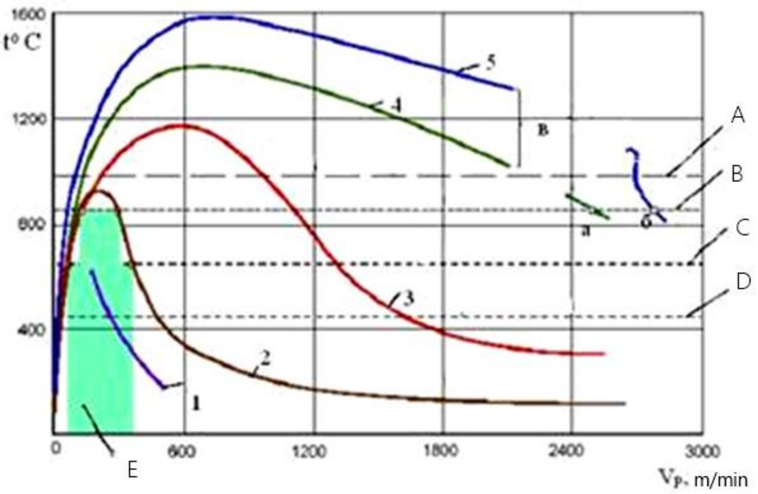


Figure 3.1.3. Dependence of temperature on cutting speed: 1 - aluminium; 2 - non-ferrous metals; 3 - bronze; 4 - foundry cast irons; 5 - steels. Tools: A - tungsten carbide: 980 oC; B - tungsten-cobalt alloys: 850 oC; C - tungsten steels: 650 oC; D - carbon steel: 450 oC; E - processing is not recommended; a - 39000 m / min; b - above 45000 m / min; c - iron-carbon alloys.

Compared to traditional methods, high-speed milling offers significant advantages:

- Reduction of cutting forces by 30% or more, which reduces deformation of parts and allows for precise machining of thin-walled structures.
- Reducing the temperature of the workpiece.
- Improved surface quality to a level comparable to abrasive machining.
- Machining accuracy is maintained longer due to reduced stress in the machine and tool.
- The feed rate can be increased by 5-10 times.
- Metal removal rate increases by 3-5 times.
- Reduction of tool and workpiece vibrations.
- Reduction in tooling cost and machining time by 40-70%, as well as total costs by 20-50%.

Comparison of the parameters of traditional and high-speed milling with a palace cutter with a spherical cutting edge shape (Table 4.1.1) shows the undeniable advantage of the latter.

Table 4.1.1. Comparison of milling parameters

Milling parameters	Conventional Machining	HSM
Rotation speed, n min -1	2000	milling
Feed rate, f m/min	0,2-0,8	15-40000
Cutting depth, t mm	1-5	1,5-5
HRC hardness	<36	0,02-0,5
cutting force	high	<62
heat emission	high	low

Additional requirements for high-speed machining machines include:

- Spindle speeds of up to 40,000 rpm.
- Main drive power of more than 22 kW.
- Programmable feed rates of 40 to 60 m/min and rapid traverses of up to 90 m/min.
- Discreteness from 5 to 20 µm.
- Axial acceleration/deceleration of more than 1g.
- CNC speed from 1 to 20 ms, data exchange rate of 250 Kbps (1 ms).
- High rigidity and heat resistance of the spindle, effective cooling of the spindle bearings.
- The rigid frame of the machine is capable of absorbing vibrations, with compensation for temperature and other errors.
- Possibility to install more advanced CNC systems.

3.2 Cutting Modes and Their Optimisation

In machining, basic definitions and formulas for calculating feed rates and spindle speeds are important. Manufacturers of HSM cutting tools always provide recommended cutting conditions in their catalogues. Although pre-calculated values and catalogue data can only serve as a starting point, they should be adjusted based on practical experience and the specialist's knowledge of the specific properties of the materials being machined. Manufacturers are encouraged to use their experience to optimise cutting parameters in HSM.

Previously, it was believed that HSM machining should be performed with shallow depths of cut, but this opinion has changed with the development of CAM systems that now support HSM principles [24].

Modern machine tools with high-speed spindles and rigid and balanced cutting tools allow machining technologists to use modern strategies for creating machining paths that are significantly different from the old approaches. The cutting parameters for HSMs now vary depending on the material being machined and the type of machining, where shallow depths of cut are only typical for difficult-to-machine materials. According to a survey of six leading German cutting experts and specialists from the aviation industry comparing HSM and high-performance machining (HPM), HPM with large depths of cut offers significantly greater potential for reducing machining times.

Table 3.2.1. Cutting speeds for different materials depending on the type of processing

Material	Cutting speed (m/min)			
	Hardness	Conventional Machining	HSM - roughing	HSM - finishing
Steel 01.2	150 HB	<300	>400	<900
Steel 02.1/2	330 HB	<200	>250	<600
Steel 03.11	300 HB	<100	>200	<400
Steel 03.11	39-48 HRc	<80	>150	<350
Steel 04	48-58 HRc	<40	>100	<250
GCI 08.1	180 HB	<300	>500	<3000
Aluminum	60-75 HB	<1000	>2000	<5000
Non-ferrous alloys	100 HB	<300	>1000	<2000

Table 3.2.2. Typical cutting parameters for hardened steel

Type of processing	Cutting speed v_c (m/min)	Depth of cut a_p (%) *	Cutting width a_e (%) *	Feed rate per tooth f_z (mm/tooth)
Roughing	50-100	30-150	10-40	0.01-0.1
Semi-finishing	150-200	5-20	5-30	0.015-0.15
Finishing and superfinishing	200-250	1-3	1-2	0.01-0.2
* As a percentage of the cutter diameter				

Table 3.2.3. Cutting speeds of various materials

Material	Cutting speed (m/min)	Cooling
Aluminum	1000-5000	Coolant or oil mist
Brass	1000-2500	Coolant or oil mist
Copper	600-1500	Coolant or oil mist
Titanium alloy	50-150	Coolant or oil mist
Graphite	1000-4000	Compressed air
Carbon fibres	250-500	Compressed air
Plastics	300-1000	Compressed air
Steels	300-700	Coolant or oil mist
Cast iron	500-750	Coolant or oil mist
Heat-resistant steel	75-100	Coolant or oil mist

For the most difficult to machine materials, the feed rate per tooth can be calculated using the formula $fz = 0.01D$. This value is perfectly suitable for all types of machining and can be increased or decreased depending on the result obtained in practice, but it is recommended that it remains within the following range: $0.005D < fz < 0.02D$, where D is the nominal diameter of the cutter in mm [25].

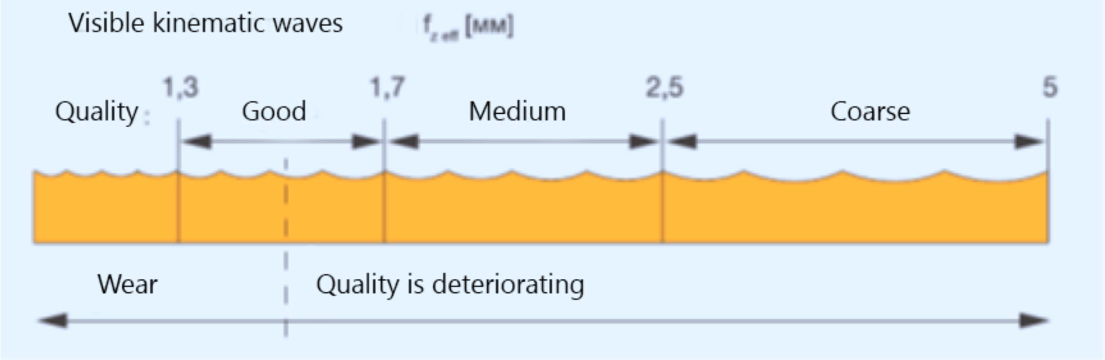


Figure 3.2.1. The relationship between the quality of the treated surface and the kinematic wavelength fz eff

The feed rate depends on the specified processing quality, which is determined by the wavelength of the kinematic waves on the treated surface.

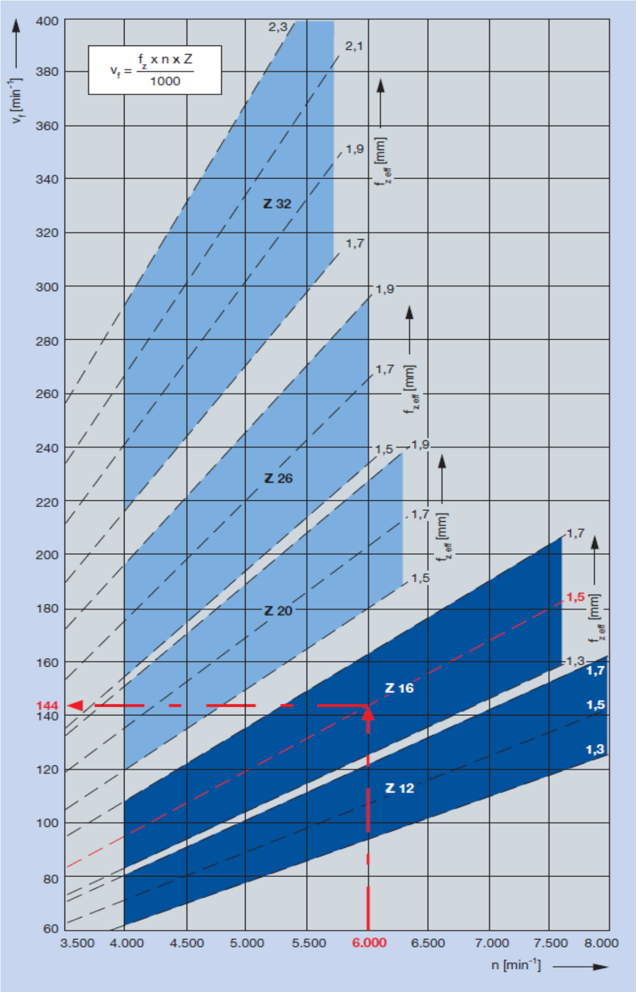


Figure 3.2.2. Calculation of the speed as a function of rotational speed n and kinematic wavelength fz eff for different number of teeth

When working with a profiled tool, all cutting edges leave the same distance of traces on the workpiece. The use of a larger number of teeth allows for higher feed rates while maintaining the quality of the workpiece.

HSM machining is usually performed without the use of a coolant. The geometry of high-speed milling cutters is designed to facilitate efficient chip removal. It is more beneficial for the tool to maintain a consistently high temperature than to be subjected to fluctuations that can be caused by a coolant. Although the emulsion is not required for cooling during HSM, its lubricating properties are often necessary [24].

When machining soft materials such as aluminium alloys or mild steel, the coolant emulsion helps to ensure that chips slide along the cutting edge without heat transfer. This is also useful when using a spherical tool, where cutting takes place at the top of the cutter, where the cutting speed on the tool axis is zero.

At shallow depths of cut, hot material can weld to the tool, which can have a negative impact on the quality of the machined surface. The use of a coolant emulsion (or oil mist) helps to minimise this effect. The use of a water-based coolant becomes more relevant when cutting speeds are reduced during HSM machining.

The use of oil mist with high-pressure blowing has proven to be the most effective during HSM. In this case, the oil must be of organic origin and safe for health.

3.3 Optimization of High-Speed Machining Process

In modern production, the cutting process plays a key role in increasing productivity while ensuring the required dimensional accuracy of parts and the specified surface quality parameters. There are two main approaches to quality control: adjusting the cutting modes during machining and achieving the required parameters through post-processing. The first method is more efficient because it often avoids additional finishing operations. Various models are developed to ensure the specified surface properties. For example, work [26] discusses adaptive control systems (ACS) that control CNC-based processing equipment.

A model has been created that allows controlling the quality of the surface layer of a part by changing the temperature of the part surface and cutting forces during high-speed face milling

(HFM). This requires determining the functional relationships between surface layer quality parameters and cutting temperature or forces, as well as the dependencies of these parameters on cutting modes. In order to maximise productivity while achieving the desired characteristics of the surface layer of a workpiece, a compromise must be made in the choice of cutting modes. The optimal mode for high-speed face milling is the one that provides the required roughness, hardening depth, level and depth of residual stresses, and structural and phase composition of the surface layer, while maintaining the stability of the cutting tool and achieving high productivity.

To implement this approach, technical constraints are imposed on the HFM process in the form of linear functions of the form:

$$a_1X_1 + a_2X_2 + ... + a_nX_n + b = 0 \quad (3.3.1)$$

This type of function can be logarithmically reduced to the following formulae, which are usually used to express cutting modes.

The basis for specifying the characteristics of the HFM modes is a set (system) of processes for the formation of quality parameters of the surface layer of a part. The dependencies establishing the relationship between cutting modes and machining parameters (roughness Rz, scoring H, surface layer temperature Θ and deviation from the setup size $\Sigma\Delta z$) were experimentally obtained, which differ from the dependencies characterising machining at traditional speeds.

Let's imagine an example of optimising high-speed finishing milling of hardened 9HS steel (55 HRC) with an end mill of the original design (Ø 250 mm, cutting material T15K6), cutting depth 0.1 mm, cutting width B = 30 mm. Technological limitations include:

Restriction 1 - residual stresses σ, MPa.

The surface layer of the machined part must have a field of residual stresses that does not contribute to the formation of microcracks and distortion of the part, which, after relaxation, lead to its dimensions exceeding the tolerance field. It has been experimentally established that part distortion does not occur when the residual stresses in the surface layer are $-200 \leq \sigma \leq -100$ MPa.

Hence, the restriction looks like:

$$-200 \leq \sigma(V, S, t) \leq -100 \qquad (3.3.2)$$

where: V - cutting speed, m/min, S - feed rate, mm/min, t - depth of cut, mm.

The calculation of the value of residual stresses was made on the basis of the developed theoretical model [27] by the formula:

$$\sigma = \sigma_f + \sigma_t + \sigma_{sp} + \sigma_p \qquad (3.3.3)$$

where: σ_f - residual stresses due to the force factor, σ_t - residual stresses due to the thermal factor, σ_{sp} - residual stresses due to the effect of structural and phase transformations, σ_p - residual stresses present in the part before processing.

Restriction 2 - by the value of the roughness of the treated surface Rz, µm.

Determine the value of the cutting parameters that provide the required surface roughness.

$$Rz = 3{,}55 \cdot 10\text{-}26 \cdot V1{,}11 \cdot S17{,}61 \cdot t0{,}29 \cdot [S\text{-}7{,}37]\ \lg V \qquad (3.3.3)$$

We assume $Rz \leq 6.3$ µm. Thus, the second constraint can be written in the form:

$$Rz\ (V, S, t) \leq 6{,}3\ \mu m. \qquad (3.3.5)$$

Restriction 3 - for hardening (slander) H, MPa.

We assume that the value of the surface layer tack should be in the range from 35 MPa to 60 MPa. This restriction has the following form:

$$35 \leq H\ (V, S, t) \leq 60 \qquad (3.3.6)$$

The dependence of the surface layer deflection on the cutting conditions is calculated by the following formula:

$$H = 1559{,}5 \cdot V\text{-}0{,}621 \cdot S0{,}219 \cdot T1{,}49 \cdot [S\text{-}0{,}443]\ \lg t \qquad (3.3.7)$$

Restriction 4 - on the structural and phase composition of the surface layer (heating temperature).

No structural changes shall occur due to high temperatures. It is assumed that no colour variations should occur during processing. It has been experimentally established that colour variability occurs at a cutting temperature of 230°C and above. Therefore, we set the main constraint as follows:

$$\Theta(V, S, t) \leq 230°C. \tag{3.3.8}$$

The temperature in the surface layer of the part is determined by the formula:

$$\Theta=0{,}004\cdot V^{1{,}47}\cdot S^{7{,}16}\cdot t^{0{,}33}\cdot[S^{2{,}63}]^{\lg V} \tag{3.3.9}$$

where: Θ - temperature, °C.

Restriction 5 - cutting spindle speed.

The value of the spindle speed n must not exceed the machine data sheet:

$$\begin{bmatrix} n \leq n_{max} \\ n \geq n_{min} \end{bmatrix} \tag{3.3.10}$$

Restriction 6 - deviation from the setup size ΣΔz, mm.

The deviation from the setup size should not exceed 0.03 mm, so we set the following restriction:

$$\Sigma\Delta z \leq 0{,}03 \tag{3.3.11}$$

The calculation formula for determining ΣΔz is as follows:

$$\Sigma\Delta z=586{,}14\cdot V^{-0{,}68}\cdot S^{0{,}228}\cdot t^{0{,}268} \tag{3.3.12}$$

Restriction 7 - from the feed.

The longitudinal feed rate of the machine must not exceed the range of regulated feed rates for the equipment.

$$\left[\begin{array}{l} S \le S_{max} \\ S \ge S_{min} \end{array}\right. \qquad (3.3.13)$$

The feed rates for the insert must not exceed the values recommended by the tool manufacturer. The feed rate S must be within the range recommended by the manufacturer. The following feed rates are recommended for T15K6 4-sided carbide inserts: Smin = 0.05 mm/tooth; Smax = 0.3 mm/tooth [28].

So, this restriction has the following form:

$$0.05 \text{ mm/rev} \le Sz \le 0.3 \text{ mm/rev} \qquad (3.3.14)$$

The target function for the cutting mode optimisation model is productivity. To solve the problem of optimising the process of high-speed face milling of hardened steels, a computer program was created in EXCEL, which allows finding the optimal values of cutting speed V and longitudinal feed S, depending on the mechanical properties of the material, parameters of the cutting tool and depth of cut. The mathematical determination of the optimal machining mode was carried out on a computer using the Generalised Reduced Gradient (GRG2) nonlinear optimisation algorithm. The combined effect of the above constraints imposed on the cutting process determines the range of permissible machining modes. The optimal mode corresponds to the point, where:

$$Sn \rightarrow \max. \qquad (3.3.15)$$

A graphical representation of these technological limitations and the region of optimal parameters for high-speed face milling is shown in the figure. Here y = ln n, x = ln 10 Sz. The area of permissible values is the ABCDE figure. At HFM of hardened steels with the following parameters: 9HS; end mill of the original design; cutting width B = 30 mm; cutting depth t = 0.1 mm, the optimal solution is indicated by point D in the figure, which corresponds to the following cutting modes: n = 1,585 rpm (V = 498 m/min); S = 0.2 mm/rev.

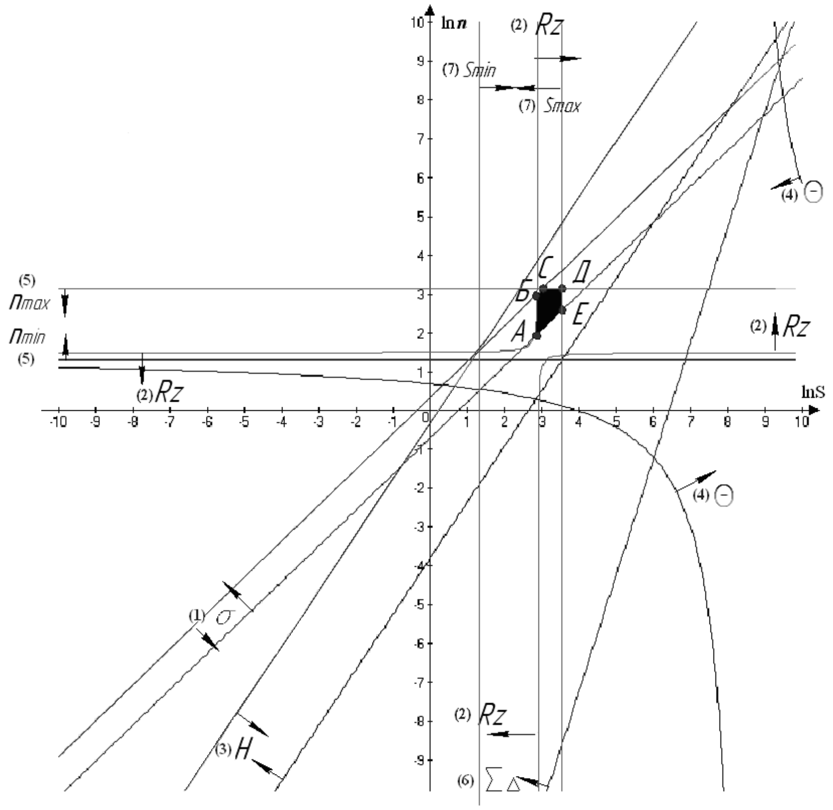


Figure 3.3.1. Mathematical representation of technological constraints of the HFM process.

The following values of the parameters of high-speed face milling of hardened steels correspond to the obtained optimal solution: residual stresses σ = -132 MPa (compressive); surface roughness Rz = 0.29 μm; surface layer peeling H = 38 MPa; cutting temperature up to θ = 21 oC above ambient air temperature.

On the basis of theoretical and experimental studies, the possibility of obtaining a surface layer of a part with specified values of residual stresses, roughness, microhardness, structural-phase composition and inhomogeneity of properties is substantiated. The range of permissible modes of high-speed face milling is determined and their optimal values are found.

3.4 3D Modeling of Parts and Machining Process Design Using CAM Systems

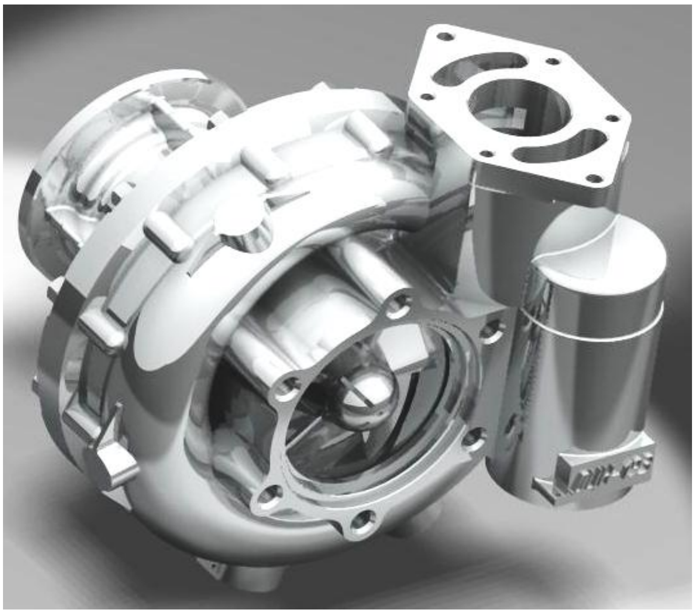


Figure 3.4.1 Assembly of a centrifugal pump casing in a CAD system

At the initial stage, a new technological process (TP) was developed for the manufacture of key pump housing components. These parts have complex geometries and play an important role in the aircraft fuel system. For the first time, the project used high-end CAD/CAM control software to produce such components. Previously, less productive machines and tools were used, which did not meet the production time and quality required by the customer. To ensure high accuracy and quality of machining, a 5-axis Multicut machine (Figure 3.4.2), SCHUNK tooling, and cutting tools from Korloy, Hoffmann, SECO, and Mitsubishi were selected. When developing the TP for each operation, the appropriate machine tool equipment, fixtures, cutting and measuring tools were selected, cutting modes were calculated, and adjustments were made according to the tool manufacturer's reference books. Based on this, the optimal machining conditions were determined, operations were normalised and the main technical and economic indicators were calculated.

Figure 3.4.2 Multi-axis turning and milling machining centre

The basis of the problem is the part in Figure 3.4.3, which has key structural elements and important mating surfaces. To shape these complex surfaces, it is advisable to use 4- and 5-axis machining.

Tasks include:

- modelling all complex surfaces and structures in PowerSHAPE based on drawings provided by the manufacturer;
- creation of a machining TP and NC file in PowerMILL;
- development and testing of a post-processor in PMPost for the Multicut machine;
- testing the results of calculations of the control programme for machining the pump unit.

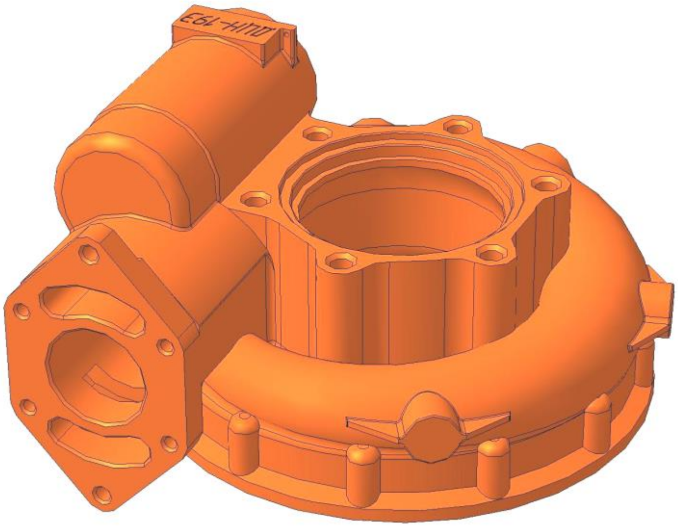


Figure 3.4.3 Basic part of a centrifugal pump

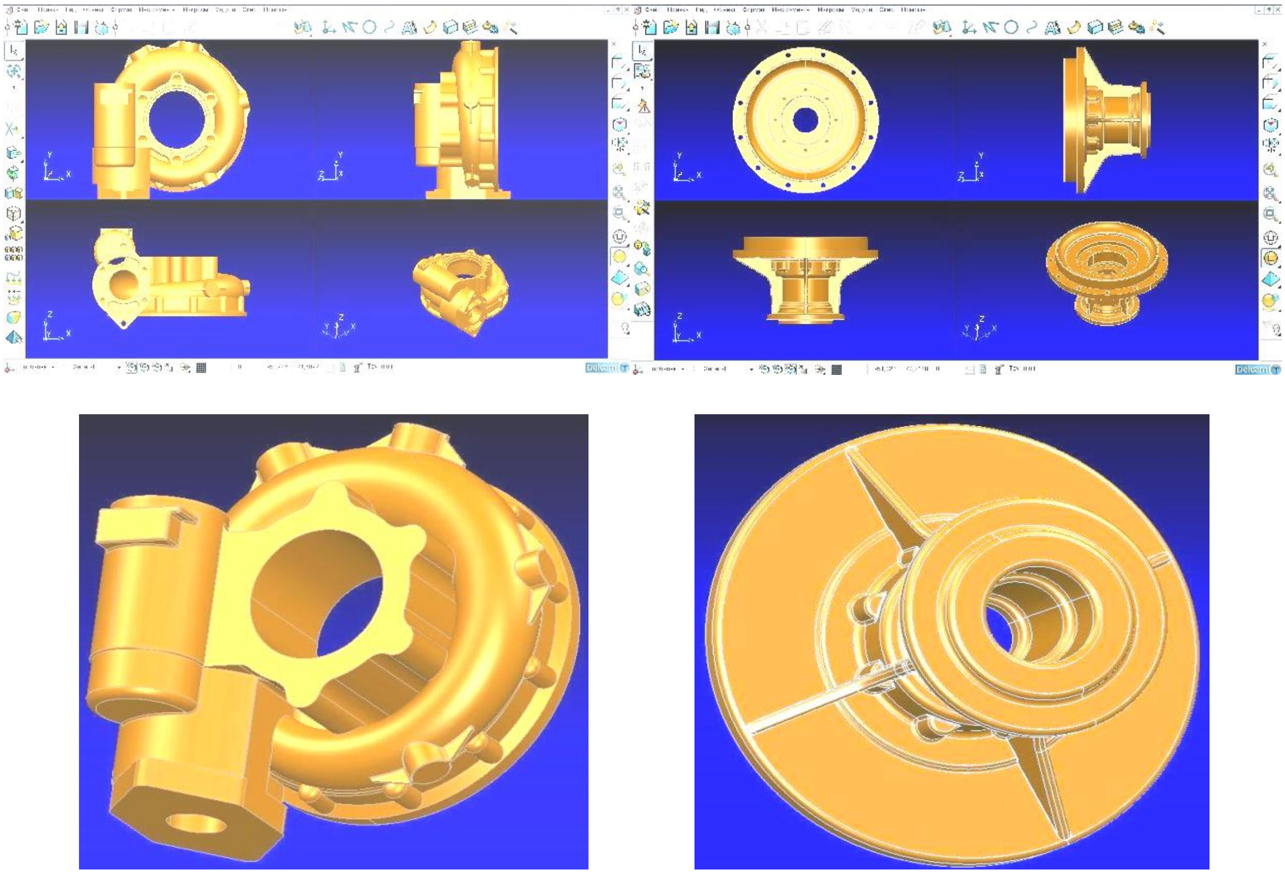


Figure 3.4.4 Workpieces

A SCHUNK polygonal thermal mandrel was used to clamp the tool during milling on the Multicut. This tooling was chosen due to the complexity of the geometric shape of the internal surfaces of the part, which includes a spiral channel with a variable diameter (Figure 3.4.5).

It was necessary to avoid tool contact with machine components and to prevent tool contact with the side surfaces of the parts, which could lead to rejects not only for the individual part but also for the entire batch due to errors in the control programme (CP). This type of mandrel is highly functional and allows you to quickly adapt your workflow to different tools using a wide range of tool shank diameters. Thanks to the modular bushings that extend the mandrel and provide an accuracy of up to 0.003 mm, short cutting tools can be used while maintaining the necessary rigidity during high-speed milling and avoiding bending of the cutter due to its long overhang.

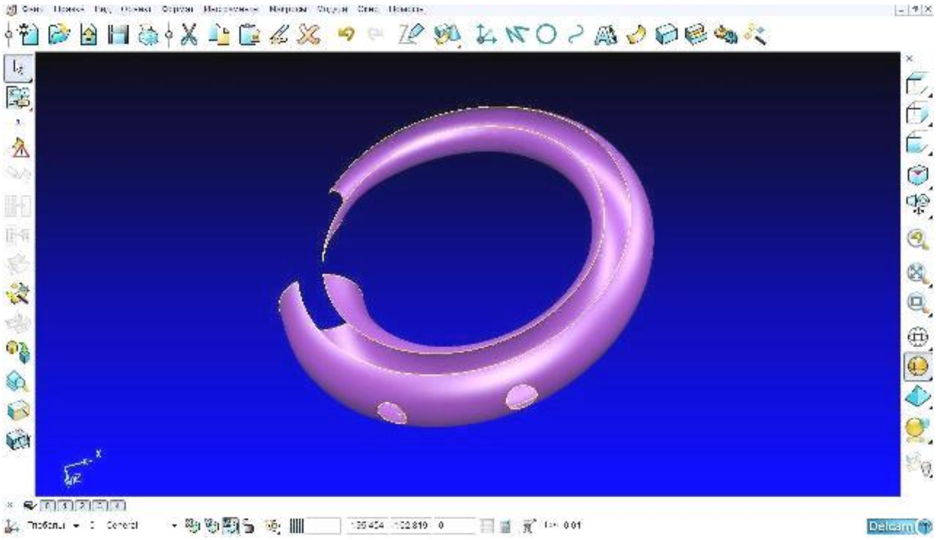


Figure 3.4.5 Spiral channel

When the mandrel is assembled from bushings, it is possible to machine deep channels with complex geometry using a ball mill (Figure 3.4.6), albeit a short one. At the same time, maintaining the rigidity of the system and the quality of the machined surface.

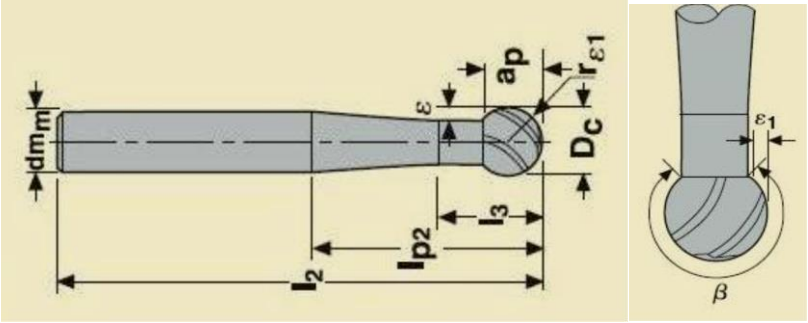


Figure 3.4.6 Ball milling cutter - carbide (finishing)

Part processing technology in PowerMILL

The technology has been redesigned to take into account the new capabilities of the machine, equipment, RI and CAD, i.e. PowerMILL. The route of part processing and the route of surface processing is as follows:

Operation 01 Roughing and finishing of the end face, for flange - Cutter Ø50 R220.29-0050-10.4A, mandrel - VT50SEMC22- 100, insert - RPHT2006MOT-ME12, F40M grade;

Operation 02 Finishing of two channels - Radial cutter Ø10 AQXR404SA10S, insert - QOGT2062R-G1, VP15TF grade;

Operation 03 Roughing and finishing of centre hole Ø40 for flange - Cutter Ø20 AQXR204SA20L, insert - QOMT1035R-M2, VP30RT;

Operation 04 Drilling holes in a Ø4.92 face - Drill bit Ø4.92 ELC4JCD1800, TF 15;

Operation 05 Drilling holes in Ø6.00 face - Drill bit Ø6 ELC4JCD1800, TF 15;

Operation 06 Roughing and finishing of the end face, under the cover - Cutter Ø50 R220.29-0050-10.4A, mandrel VT50SEMC22- 100, insert RPHT2006MOT-ME12, F40M grade;

Operation 07 Drilling holes in Ø6.00 threaded end face - Drill bit Ø6 ELC4JCD1800, TF 15; (12 holes);

Operation 08 Threading a M7x1 end face - M7 tap ELC4JCD1800, TF 15; (12 holes);

Operation 09 Roughing the internal cavity of the part for the cover - Cutter Ø15 AQXR204SA15L, insert - QOMT1035R-M2, VP30RT grade;

Operation 10 Semi-finishing and finishing of the spiral channel - Cutter Ø13 AQXR204SA13L, insert - QOMT1035R-M2, VP30RT grade; (SPECIAL)

Operation 11 Roughing and finishing of the end face, under the nozzle - Cutter Ø30 R220.29-0030-10.4A, mandrel - VT50SEMC22- 100, insert - RPHT2006MOT-ME12, F40M grade;

Operation 12 Drilling holes in the Ø10.5 end face for M12x1.5 threads - Drill bit Ø10.5 ELC4JCD1800, TF 15; (6 holes);

Operation 13 Threading an end face for M12x1.5 - M12 tap ELC4JCD1800, TF 15; (6 holes);

Operation 14 Engraving. The name of the pump ‘ДЦН-19Е’ is an engraving cutter Ø1.5 ES-V6200-76C20-104, alloy IC 903.

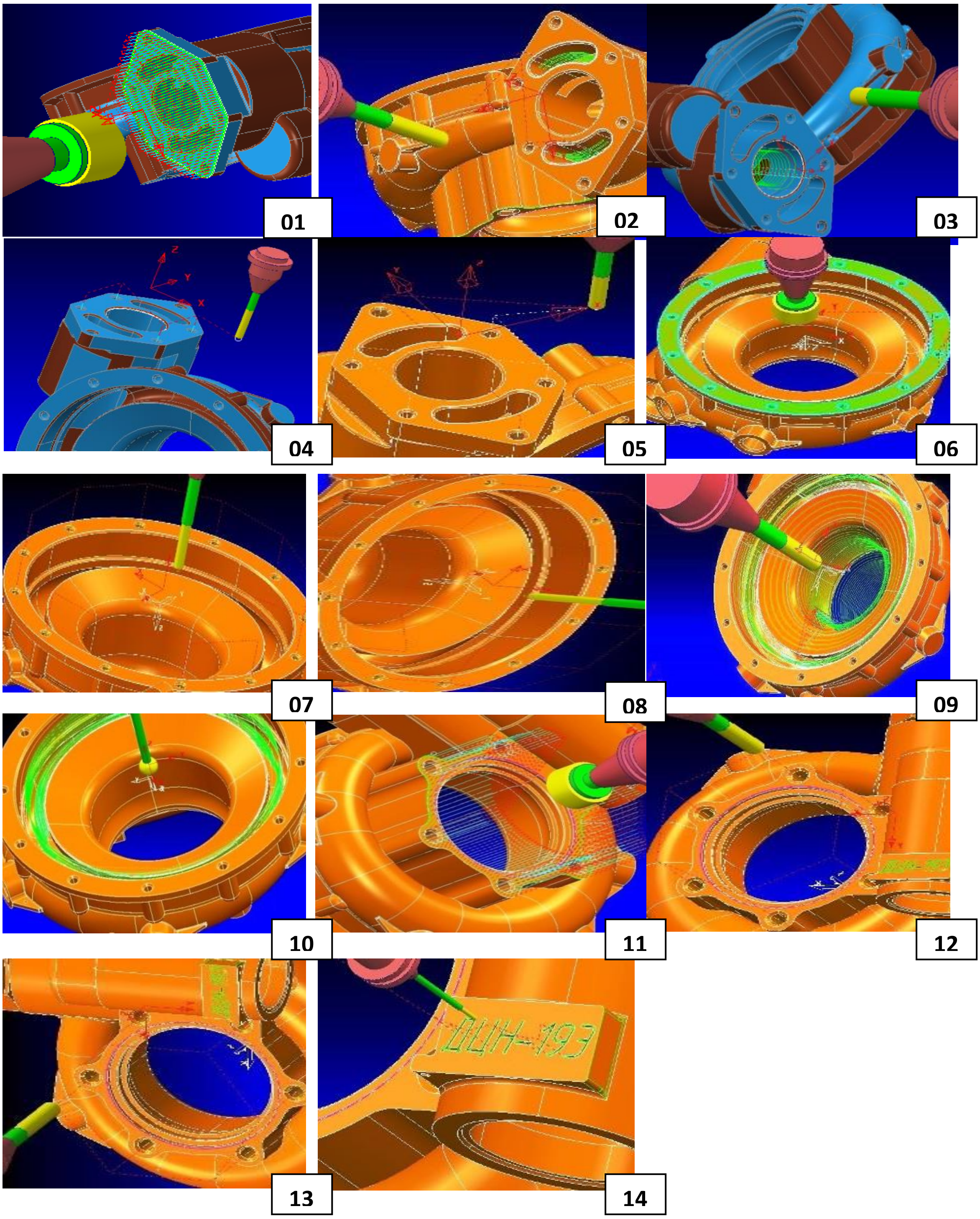
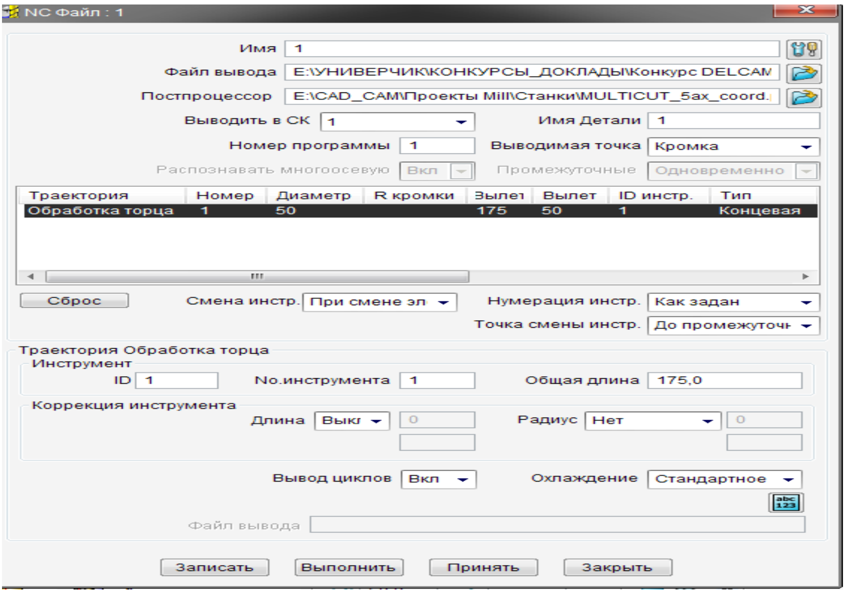


Figure 3.4.7 Surface machining route of the workpiece

Using a standard postprocessor, this session is saved to an option file with the extension '.pmopt' and imported into the NC file window of the PowerMILL software (Figure 3.4.8). At this stage, the technology is complete, the created file-code is ready for use and can be sent to the machine tool rack.


NC Файл : 1

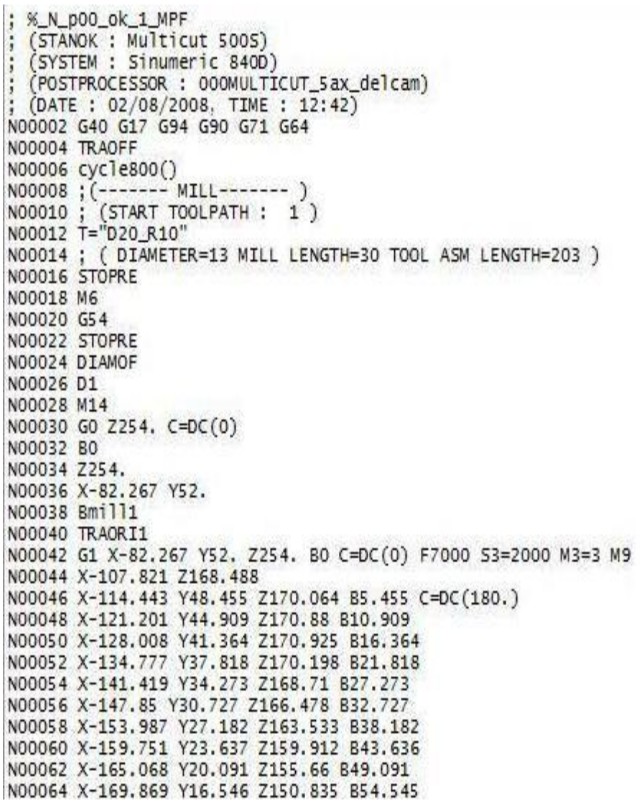
Имя 1
Файл вывода E:\УНИВЕРЧИК\КОНКУРСЫ_ДОКЛАДЫ\Конкурс DELCAM
Постпроцессор E:\CAD_CAM\Проекты Mill\Станки\MULTICUT_5ax_coord.
Выводить в СК 1
Имя Детали 1
Номер программы 1
Выводимая точка Кромка
Распознавать многоосевую Вкл
Промежуточные Одновременно

Траектория	Номер	Диаметр	R кромки	Вылет	Вылет	ID инстр.	Тип
Обработка торца	1	50		175	50	1	Концевая

Смена инстр. При смене эл
Нумерация инстр. Как задан
Точка смены инстр. До промежуточн

Траектория Обработка торца
Инструмент
ID 1
No.инструмента 1
Общая длина 175,0
Коррекция инструмента
Длина Выкл 0
Радиус Нет 0
Вывод циклов Вкл
Охлаждение Стандартное
Файл вывода

Figure 3.4.8 Recording an NC file



```
; %_N_p00_ok_1_MPF
; (STANOK : Multicut 500S)
; (SYSTEM : Sinumeric 840D)
; (POSTPROCESSOR : 000MULTICUT_5ax_delcam)
; (DATE : 02/08/2008, TIME : 12:42)
N00002 G40 G17 G94 G90 G71 G64
N00004 TRAOFF
N00006 cycle800()
N00008 ;(------- MILL------- )
N00010 ; (START TOOLPATH :  1 )
N00012 T="D20_R10"
N00014 ; ( DIAMETER=13 MILL LENGTH=30 TOOL ASM LENGTH=203 )
N00016 STOPRE
N00018 M6
N00020 G54
N00022 STOPRE
N00024 DIAMOF
N00026 D1
N00028 M14
N00030 G0 Z254. C=DC(0)
N00032 B0
N00034 Z254.
N00036 X-82.267 Y52.
N00038 Bmill1
N00040 TRAORI1
N00042 G1 X-82.267 Y52. Z254. B0 C=DC(0) F7000 S3=2000 M3=3 M9
N00044 X-107.821 Z168.488
N00046 X-114.443 Y48.455 Z170.064 B5.455 C=DC(180.)
N00048 X-121.201 Y44.909 Z170.88 B10.909
N00050 X-128.008 Y41.364 Z170.925 B16.364
N00052 X-134.777 Y37.818 Z170.198 B21.818
N00054 X-141.419 Y34.273 Z168.71 B27.273
N00056 X-147.85 Y30.727 Z166.478 B32.727
N00058 X-153.987 Y27.182 Z163.533 B38.182
N00060 X-159.751 Y23.637 Z159.912 B43.636
N00062 X-165.068 Y20.091 Z155.66 B49.091
N00064 X-169.869 Y16.546 Z150.835 B54.545
```

Figure 3.4.9 Fragment of the NC file for a CNC machine

Conclusions to the chapter:

1) A new generation CAD/CAM system has been used to process the complex geometry of shaped surfaces of aircraft pumps.

2) The use of Autodesk Fusion with PowerMill and PowerShape software helps to improve the accuracy of the geometry of shaped surfaces and the quality of their surface layer.

3) The introduction of new structural and tool materials and their implementation in the development of modern high-tech production of aircraft parts has significantly improved the functional, aesthetic and environmental characteristics of products, while improving the quality of the relief and ensuring defect-free surface layer.

4) This project ensures high economic, quality and technological performance, which will have a favourable impact on the profitability of these products both in Ukraine and abroad.

3.5 Additive Manufacturing for Centrifugal Pump Casing

This chapter will provide a more detailed overview of the process described in 2.5 for the part under review, namely casing for the centrifugal pump DCN-19E (or MCP-19, which stands for "Motor Centrifugal Pump").

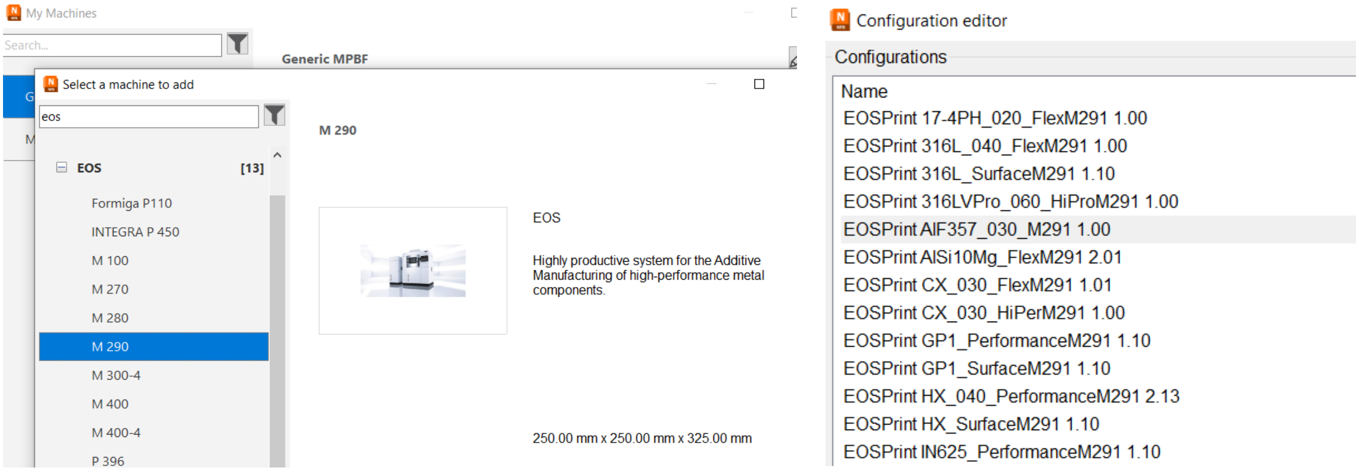
The process begins with the selection of an appropriate SLM machine. The EOS M 290 was chosen as it is a high-end SLM machine that is well-suited for the production of complex metal parts. This machine is highly compatible with the chosen powder (F357 or AlSi7Mg). The production process requires the setup of several key parameters. Following parameters are recommended by the manufacturer for that particular alloy:

- Layer Thickness (30 µm)
- Volume Rate (5.8 mm^3/s): This parameter controls the rate at which material is deposited and solidified.
- Laser Power (400 W)
- Scan Speed (1300 mm/s)
- Hatch Spacing (0.13 mm): Hatch spacing refers to the distance between adjacent laser scan lines.

Additionally, the selected machine employs an inert gas environment (in that case

Nitrogen) to prevent oxidation of the aluminum powder during melting. This is important for aluminum powder alloys to avoid the formation of oxide inclusions that can compromise the part's strength.

When importing the part into Netfabb, the machine to use can be selected, including M290 as an option. The same process applies to the material, with F357 available for use with M290 and already selectable from the list of materials. Degree of tessellation can also be selected.



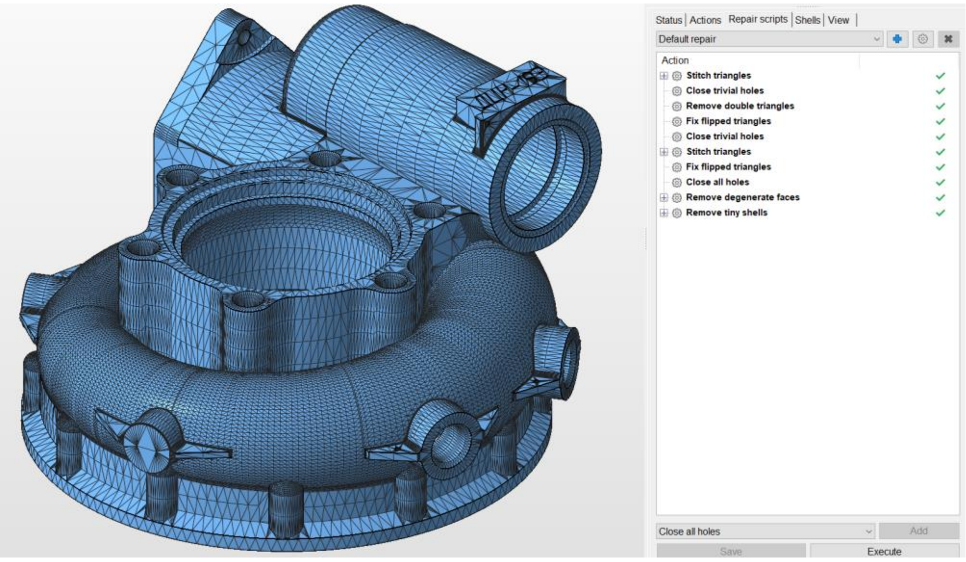
Highly productive system for the Additive Manufacturing of high-performance metal components.

250.00 mm x 250.00 mm x 325.00 mm

EOSPrint 17-4PH_020_FlexM291 1.00
EOSPrint 316L_040_FlexM291 1.00
EOSPrint 316L_SurfaceM291 1.10
EOSPrint 316LVPro_060_HiProM291 1.00
EOSPrint AlF357_030_M291 1.00
EOSPrint AlSi10Mg_FlexM291 2.01
EOSPrint CX_030_FlexM291 1.01
EOSPrint CX_030_HiPerM291 1.00
EOSPrint GP1_PerformanceM291 1.10
EOSPrint GP1_SurfaceM291 1.10
EOSPrint HX_040_PerformanceM291 2.13
EOSPrint HX_SurfaceM291 1.10
EOSPrint IN625_PerformanceM291 1.10

Figure 3.5.1 Machine and Material Selection

Once the part has been imported into the program, it is recommended that a mesh repair is performed. This can be done manually, but it is faster and more efficient to use an automated script included in the software. Manual adjustments can then be made if necessary to ensure optimum quality.



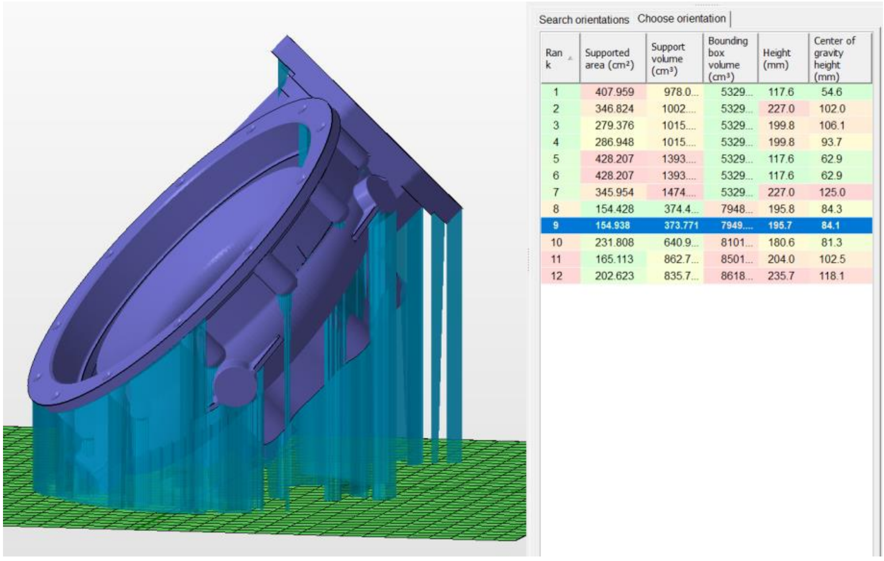
Stitch triangles ✓
Close trivial holes ✓
Remove double triangles ✓
Fix flipped triangles ✓
Close trivial holes ✓
Stitch triangles ✓
Fix flipped triangles ✓
Close all holes ✓
Remove degenerate faces ✓
Remove tiny shells ✓

Figure 3.5.2 Repaired mesh with the list of actions

After repairing the mesh, next step would be packing.

Once the mesh repair is complete, the next step is to prepare the parts for printing. The build volume of the EOS M290 machine is 250x250x325mm, which can accommodate up to three parts, each measuring 211.65x205.73x130.29mm when tilted slightly. However, vertical stacking of parts in SLM is generally not advisable, especially for parts with complex geometries. This is due to potential problems such as uneven thermal gradients, which can lead to thermal stress, distortion and compromised mechanical properties. Stacking also requires additional support structures, which increases material usage and complicates post-processing. In addition, stacked parts are more susceptible to surface finish problems and contamination from trapped powder, resulting in defects.

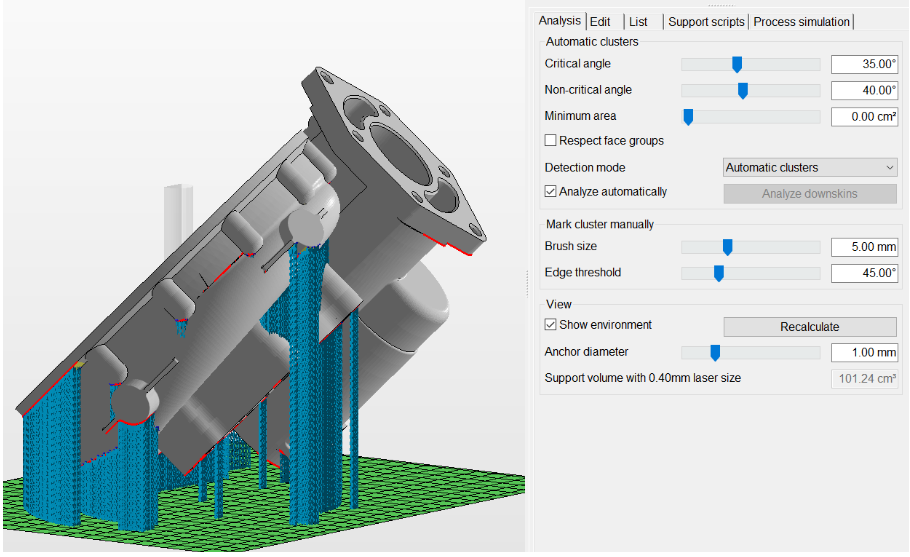
With these considerations in mind, it was decided to print each part individually with optimised orientation and support structures. To achieve optimal part orientation within the build space, the "orient parts" script in Netfabb is used. This script provides several orientation options ranked by parameters such as supported area, support volume, bounding box volume, height and centre of gravity height.



Rank	Supported area (cm²)	Support volume (cm³)	Bounding box volume (cm³)	Height (mm)	Center of gravity height (mm)
1	407.959	978.0...	5329...	117.6	54.6
2	346.824	1002....	5329...	227.0	102.0
3	279.376	1015....	5329...	199.8	106.1
4	286.948	1015....	5329...	199.8	93.7
5	428.207	1393....	5329...	117.6	62.9
6	428.207	1393....	5329...	117.6	62.9
7	345.954	1474....	5329...	227.0	125.0
8	154.428	374.4...	7948...	195.8	84.3
9	154.938	373.771	7949....	195.7	84.1
10	231.808	640.9...	8101...	180.6	81.3
11	165.113	862.7...	8501...	204.0	102.5
12	202.623	835.7...	8618...	235.7	118.1

Figure 3.5.3 Part orientation and available options.

An orientation ranked as option 9 was selected because it minimises the support volume, thereby reducing powder consumption. This orientation also minimises the number of supports on critical surfaces such as mating surfaces and internal fluid channels, therefore simplifying mechanical post-processing. Support structures can be generated either manually or using the integrated scripting tools provided for various applications.



Automatic clusters
Critical angle 35.00°
Non-critical angle 40.00°
Minimum area 0.00 cm²
☐ Respect face groups
Detection mode Automatic clusters
☑ Analyze automatically

Mark cluster manually
Brush size 5.00 mm
Edge threshold 45.00°

View
☑ Show environment
Anchor diameter 1.00 mm
Support volume with 0.40mm laser size 101.24 cm³

Figure 3.5.5 Generated structures and parameters

Once the support structures have been created, the slicing process begins. Slicing is essential to define the layers of the build and can be performed using Netfabb's built-in slicing script. By entering the desired layer thickness (30µm or 0.03mm) the software slices the part accordingly.

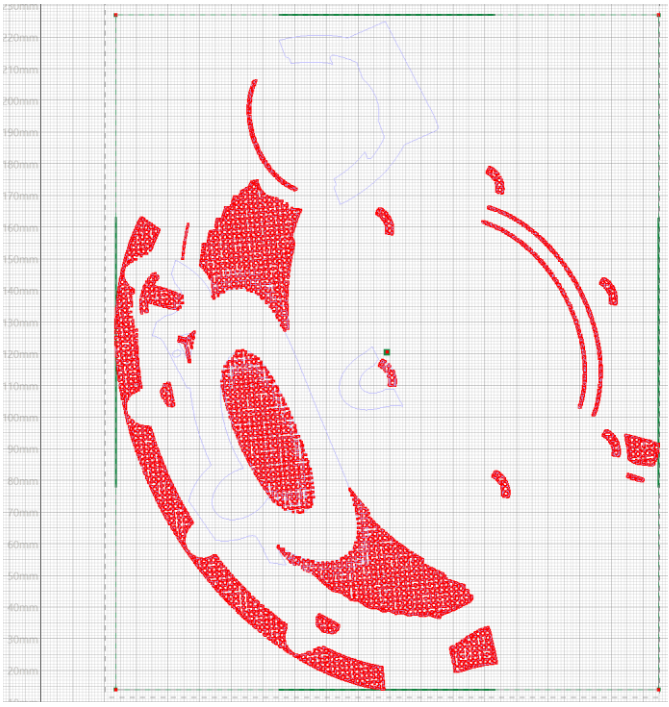
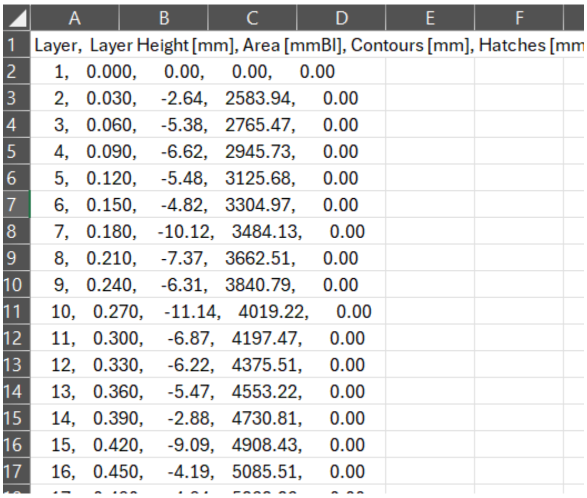


Figure 3.5.6 Slice 662 out of 6626

The toolpath and selected layer are visible in the section view, where manual adjustments can be made. Within this view, users can create offsets or fills, reinforce thin walls and modify hatch patterns. Slice information can also be exported as a .csv file for further analysis.



	A	B	C	D	E	F
1	Layer, Layer Height [mm], Area [mmBl], Contours [mm], Hatches [mm					
2	1, 0.000, 0.00, 0.00, 0.00					
3	2, 0.030, -2.64, 2583.94, 0.00					
4	3, 0.060, -5.38, 2765.47, 0.00					
5	4, 0.090, -6.62, 2945.73, 0.00					
6	5, 0.120, -5.48, 3125.68, 0.00					
7	6, 0.150, -4.82, 3304.97, 0.00					
8	7, 0.180, -10.12, 3484.13, 0.00					
9	8, 0.210, -7.37, 3662.51, 0.00					
10	9, 0.240, -6.31, 3840.79, 0.00					
11	10, 0.270, -11.14, 4019.22, 0.00					
12	11, 0.300, -6.87, 4197.47, 0.00					
13	12, 0.330, -6.22, 4375.51, 0.00					
14	13, 0.360, -5.47, 4553.22, 0.00					
15	14, 0.390, -2.88, 4730.81, 0.00					
16	15, 0.420, -9.09, 4908.43, 0.00					
17	16, 0.450, -4.19, 5085.51, 0.00					

Figure 3.5.7 CSV Slice Info

Once all the preparatory steps have been completed, the build simulation can be initiated. A dedicated simulation utility in Netfabb is used to configure parameters such as processing settings, material selection, part orientation, build plate settings, mesh settings and heat treatment protocols.

Conventionally cast components in this type of aluminium alloy are often heat treated using a T6 cycle consisting of solution annealing, quenching and age hardening and since our maximum output pressure is no more than 784 kPa, T6 should suffice [29]. A T6 type heat treatment has been specifically designed to increase the ductility and yield strength and reduce the anisotropy of the components, consisting of the following cycles:

1. Solution annealing:

30 minutes at 540°C (±6°C) measured from the part, followed by immediate quenching in water at room temperature.

2. Aging:

6 hours at 165 °C (±6 °C) measured from the part, followed by air cooling.
After inputting all the necessary parameters, and solving the simulation (which can last up to couple of days, depending on hardware) in my case it took almost 17 hours.

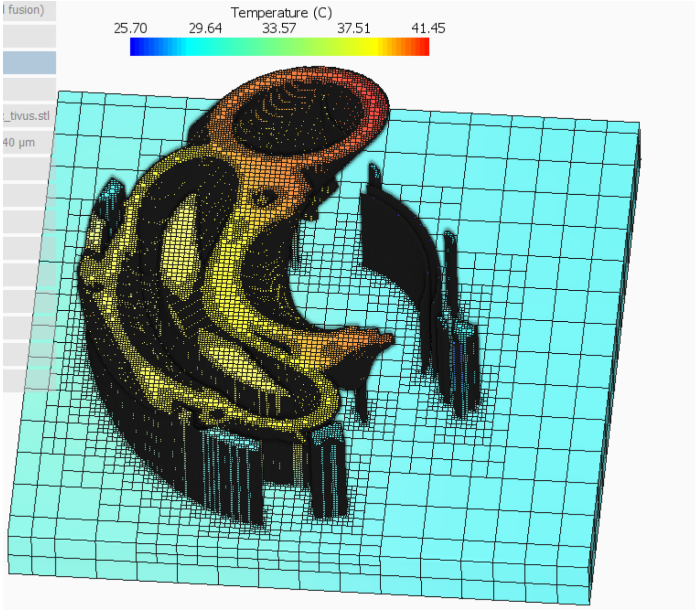


Figure 3.5.8 Build Simulation ~25% done

The simulation results showed no build failures, with an estimated total print time of approximately 64 hours. In addition, various result types were configured to be generated during the simulation process through the solver settings.

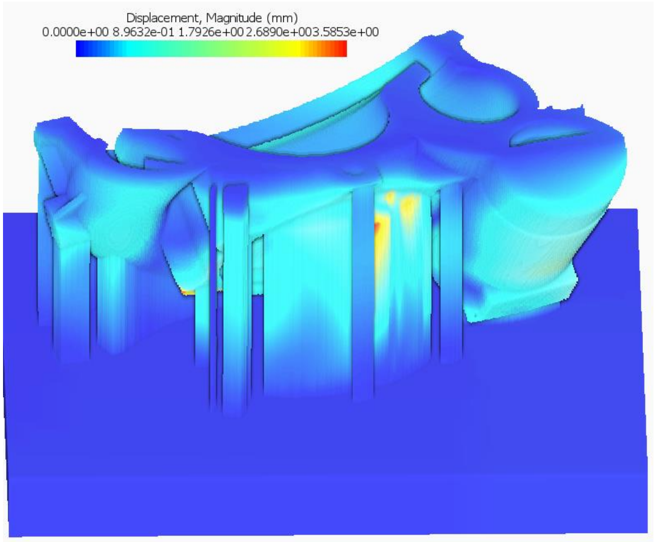


Figure 3.5.9 Displacement simulation ~60% done

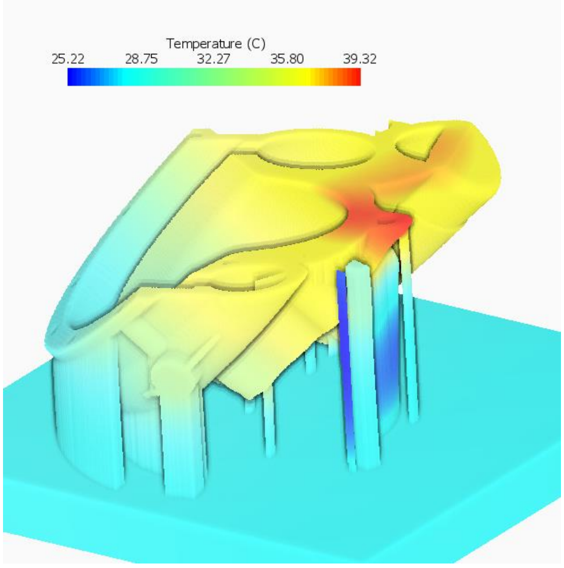


Figure 3.5.10 Temperature ~60% done

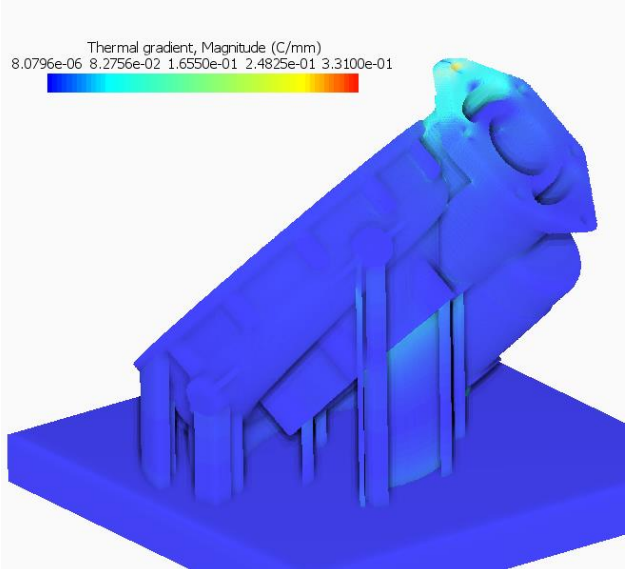


Figure 3.5.11 Temperature gradient 100% done

The principal stress and plastic strain simulations showed no significant problems, confirming the viability of the structure under the chosen parameters.

Some operations from chapter 3.4 must be repeated to ensure proper quality of faces, threads and fluid channel, namely:

- Critical faces – Operations 1, 6 and 11.
- Threads – Operations 8 and 13
- Channel – Operation 10

Conclusions to the chapter:

1. The EOS M 290 SLM machine, with its precise parameters and inert gas environment, could be used to effectively produce complex pump casings with high mechanical integrity and minimal oxidation.
2. Autodesk Netfabb software optimised the build process through efficient mesh repair, alignment and support structure generation, reducing material waste and post-processing time.
3. Simulation results confirmed the reliability of the chosen process, with no build failures validating the suitability of the SLM process.
4. Incorporating additive manufacturing into the production of pump casings can improve efficiency, reduce costs and supports sustainable practices, providing a competitive advantage in the marketplace.

GENERAL CONCLUSIONS

Both high-speed machining (HSM) and additive manufacturing (AM) have their unique advantages and disadvantages when considered within the context of circular economy (CE). HSM is highly effective for high-volume production and producing parts with excellent surface finishes, particularly for durable components such as pump housings. However, it is a subtractive process that generates significant waste in the form of chips. To comply with CE principles, these waste materials must be efficiently recycled. The use of recycled materials can reduce the environmental impact, but the quality of these materials must meet the high standards required for industrial applications.

In contrast, AM, particularly Selective Laser Melting (SLM), is naturally more sustainable due to its layer-by-layer approach, which minimises material waste by using only the required amount of powder. It also enables the design of complex geometries that are difficult to achieve with traditional methods, such as optimised internal flow paths for centrifugal pump casings, thereby improving operational efficiency. AM also supports the use of recycled powders, reducing the need for virgin materials and promoting the reuse of resources, which is closely aligned with CE objectives. However, AM is energy intensive, particularly due to the power requirements of the lasers and the need for inert gas environments to prevent oxidation. Post-processing steps such as heat treatment and surface finishing further increase energy consumption, posing a challenge to overall sustainability.

From an economic point of view, AM's long print times make it less suitable for mass production than traditional methods. For example, a single part that takes approximately 64 hours to print is not economically viable for mass production given the cost of the SLM machine and software investment. On the other hand, although traditional casting methods have a higher initial carbon footprint due to energy-intensive processes, they can be more efficient for high-volume production because they require fewer CNC operations to achieve the desired properties, reducing overall production costs and time.

Integrating both HSM and AM within a CE framework provides a balanced approach. AM is ideal for rapid prototyping and low-volume production of complex parts, while HSM is more suited to finishing operations or the production of high-volume components from recycled materials.

By adopting this combined approach, manufacturers can effectively address both environmental and economic challenges, in line with the goals of the circular economy to minimise waste, reduce carbon emissions and optimise resource use.

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Declaration of Originality

I confirm that the submitted thesis is original work and was written by me without further assistance. Appropriate credit has been given where reference has been made to the work of others.

The thesis was not examined before, nor has it been published. The submitted electronic version of the thesis matches the printed version.

Erklärung zur Masterarbeit

Hiermit versichere ich, dass ich die von mir vorgelegte Masterarbeit

- selbständig verfasst habe,
- ich keine anderen als die in der Masterarbeit angegebenen Quellen und Hilfsmittel benutzt habe,
- ich alle wörtlich oder sinngemäß aus anderen Werken übernommenen Inhalte als solche kenntlich gemacht habe.

Des Weiteren versichere ich, dass die von mir vorgelegte Masterarbeit weder vollständig noch in wesentlichen Teilen Gegenstand eines anderen Prüfungsverfahrens war oder ist.

Ich versichere zudem, dass die von mir eingereichte elektronische Version in Form und Inhalt der gedruckten Version der Masterarbeit entspricht.

Vienna, 25.08.2024

Ort, Datum
Place, date

Unterschrift
Signature

➡ Die Erklärung wird als letzte Seite in die Masterarbeit eingefügt (also mitgebunden). Bei einer englischsprachigen Masterarbeit ist sowohl die englische als auch die deutsche Erklärung (auf dieselbe Seite) einzufügen, da sichergestellt sein muss, dass der/die Studierende die Erklärung verstanden hat.