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ROBOT-BASED HYBRID MANUFACTURING PROCESS CHAIN

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Abstract

The combination of additive and subtractive processes using an industrial robot in a hybrid production concept is an innovative approach in manufacturing technology. An improvement in the near net shape geometry production processes is achieved by using a wire-based laser metal deposition process with the added benefit of saving resources. Assisted by qualified CAM tools and an interposed laser line scanning, this process chain enables production of tool and dies, especially for automotive industry and manufacturing of parts made of nickel-based alloys for aerospace industry. This expands the workpiece material application range for robot-based milling. For the robot-machining processes, extended strategies in CAM path planning have been qualified focusing on increased machining-process quality. The system technology and sub-processes have been integrated into a robot-cell, enabling a hybrid part production process in a single workpiece clamping.

Keywords: hybrid manufacturing, industrial robots, Alloy 718, quality-loops, deep-drawing die

Introduction

The current trends regarding high-strength materials and increasingly complex component structures pose major challenges for manufacturing companies with selection and development of resource-efficient processes. From the point of view of these companies, an efficient handling of resources is essential for a successful business [1]. Since resource-saving products are often associated with additional investments and process development costs, the difficulty for operations managers is to select both economically sensible and efficient solutions. The major approaches for resource-efficient production can be identified in various areas of manufacturing. The aim of current research projects at Institute of Production Management, Technology and Machine Tools (PTW) at Technische Universität Darmstadt, Germany, is to combine the following identified potentials in a robotic machining center with additive production for a resource- and energy-efficient, near-net-shape production of components. In the following, this robot-supported process combination will be referred to as hybrid manufacturing [2]. The substitution of the translational main axes of a classical machining center by industrial robots offers greater flexibility in the machining areas at lower investment costs. Modern 6-axis robots are mainly used in the automotive industry for handling- and welding-operations. For this reason, this technology is almost cost- and consumption-optimized. Thus industrial robots represent a cost-effective alternative [3]. With regards to a comparable task and parameter setting, a milling robot system is 15 times more energy efficient compared to a machine tool [5].

Regarding the energy consumption of a machining process and its environment, the PTW conducted machining trials for turned parts at Heidelberger Druckmaschinen AG. The consumption of 1 kWh was subdivided into the different processing steps [4]. In [5] is shown that 63 % per 1 kWh is used to operate the machine tool, while further 5 % is used each in transport in shop floor and machining. Certain process chains, especially for larger components such as tool and die operations for the manufacture of deep drawing dies used in the automotive industry, are characterized by high intralogistic costs. Therefore, avoiding the transport of these tools to measuring stations or machining centers [6] offers even greater potential in the sense of avoiding waste and efficient handling of resources. Taking a look in the machining process reveals an approach to resource saving production in the sense of energy efficiency.

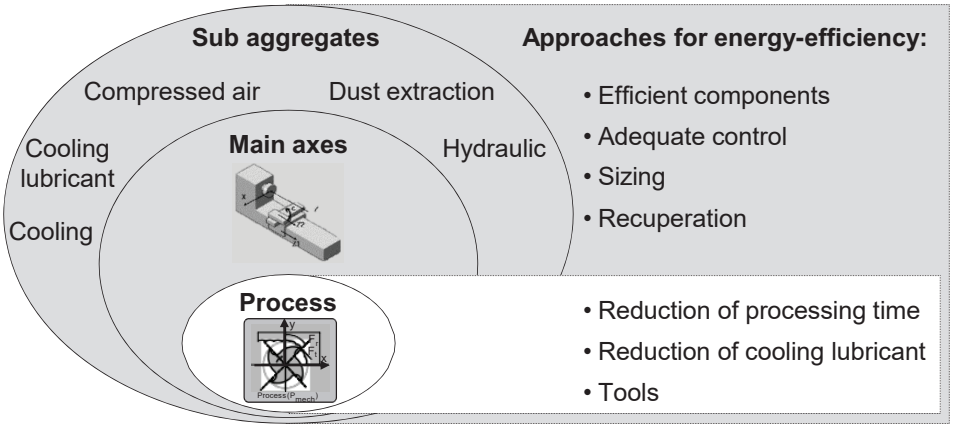

Figure 1: Approaches to increase the energy efficiency of metal cutting machine tools. Based on [4].

Figure 1 outlines the main consumers of a machining process and their potential for increasing energy-efficiency. According to Abele et al. [4] the auxiliary units, the main axes and the machining process itself provide the highest potential for energy-saving. Based upon those potentials a new method for resource- and energy-efficient production is presented in this publication by using industrial robots for hybrid manufacturing and quality assurance.

Motivation and Objectives

In addition to the economic advantages, the implementation of a robot-supported hybrid manufacturing system offers the possibility of using laser metal deposition processes on existing geometries due to the size of the machining area, which makes this technology particularly interesting for manufacturing of deep-drawing dies. By adding a tilting table to the robot-cell, process guiding can be particularly flexible and components can be manufactured in one clamping. The interlinking of the hybrid process via optical component digitization makes it possible to increase productivity through automated comparisons. This enables particularly efficient path planning for machining post-processing and overcomes production-related limitations in component design through conventional manufacturing processes. The possibility of using the system technology of a robot-supported process chain for hybrid production was part of the ProGen [7] research project, as it is depicted in Figure 2, applied to two applications.

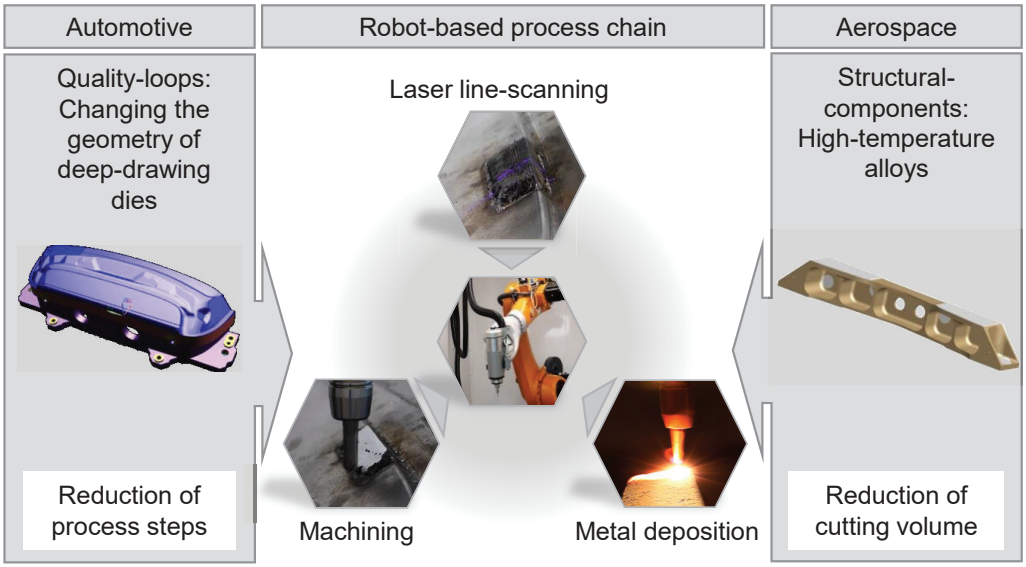

Figure 2: Robot-based process chain.

The aim of these applications is on the one hand, for the automotive industry, to shorten the quality-loop of a deep-drawing die, shown on the left side of Figure 2. On the other hand, to manufacture components made of Ni-based alloys from the aviation industry, in a resource-efficient manner. The design of the deep drawing die to be changed is shown on the left side. It consists of grey cast iron (EN-JS 1070 | ASTM A536-584 (US) 100/70/03) and has the dimensions (LWH) 1500 x 500 x 450 mm³. The main focus of this application is the reduction of process steps for a faster throughput of the quality-loop. The second application is an aerospace engine mount made of Alloy 718 which is shown on the right side and has the dimensions (LWH) 500 x 65 x 60 mm³.
A robot-based hybrid manufacturing center (HMC) was developed for the execution of these manufacturing tasks. With the realization of the HMC the following approaches are pursued:

- The further qualification of the combined interaction of the two robot-based manufacturing processes wire-based laser metal deposition (LMD) and adaptive machining (RAM) for the near-net-shape production of free-form geometries as well as the integration of a geometry acquisition process (3D scan).
- Reduction of processing time and transport routes due to the novel combination of processes in a HMC robot-cell through digitization and elimination of several individual stations.

The overall efficiency of the process is increased by means of the intelligent reduction of the cutting volume through small machining allowances in the additive process and through digitization.

State of the Art

The use case of the quality-loops in the deep-drawing die construction is explained first. Afterwards the state of the art of machining components made of nickel-based alloys for the aircraft industry is introduced.

Quality-Loops

For several years the appearance of cars is dominated by clear lines, pronounced beadings and complex geometries. This design requires a high level of process reliability in the manufacturing of deep drawing dies. The dies used for the deep drawing of car body parts with high quality requirements and low tolerances (±0.05 mm) [8] often have to be reworked before they can be used in series production. There are various reasons for the rework of the deep-drawing dies. For example, processes itself or unfulfilled quality requirements on the body part or the deep drawing die. Part of this process is the so-called quality-loop in deep drawing die construction [6]. In addition to engineering, several production stations must also be passed through in this loop. For the production period of an automobile, a die set consisting of 4 to 6 dies is required for each body part. Due to the high quality requirements, the production of these unique parts is very complex and characterized by many iterations that have to be integrated into the manufacturing process [9]. Within one pass of a quality-loop, the deep-drawn workpiece is measured before the geometry of the die is corrected by machining and deposition welding. As shown in Figure 3, this quality-loop is repeated until the desired quality of the corresponding deep-drawn part is achieved.

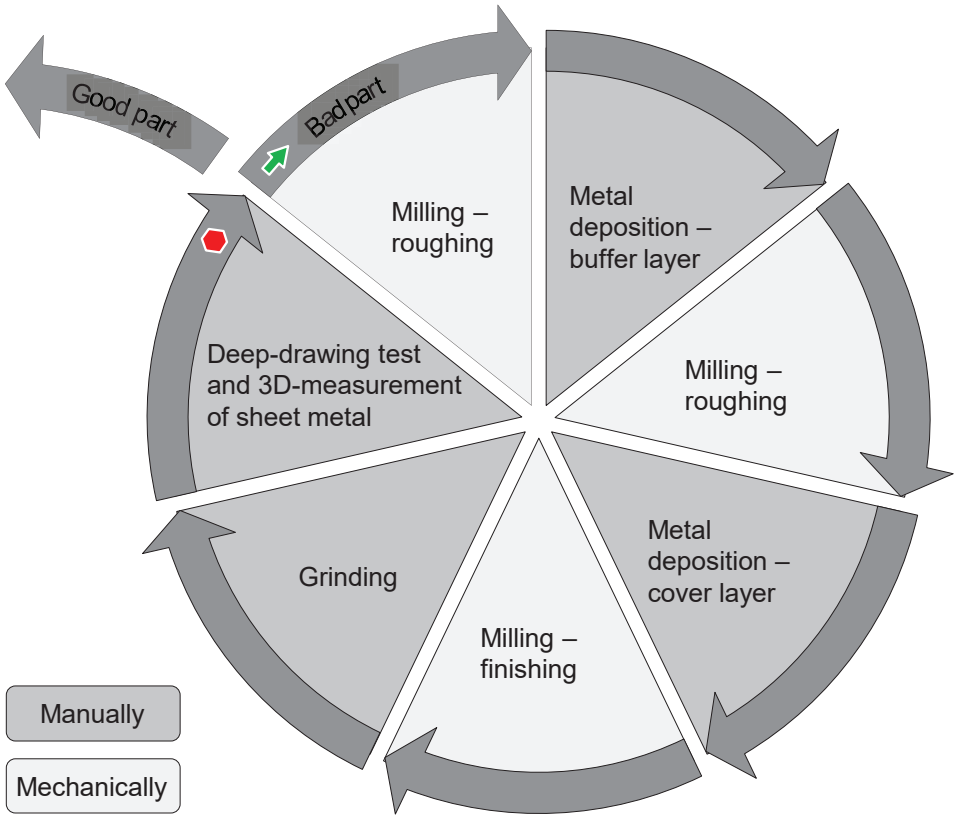

Figure 3: Quality-loop in the tool and die shop [6].

A characteristic feature of the quality-loop is the high proportion of manual processing steps, combined with high logistics and many transport operations within the tool and die shop. Since the quality-loops take place shortly before the start of series production, this process is extremely time-critical. Due to the lack of digitization possibilities in the individual production steps, especially in manual reworking, and the high tolerance requirements, the loop usually runs as often as necessary in a period of several weeks. Typical operations in reworking are the adaptation of the geometry by additive- and post processes. Figure 4 shows the modification of the geometry of a deep-drawing die of a base assembly by MIG deposition welding by hand.

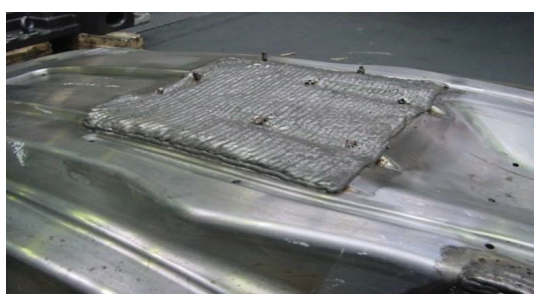

Figure 4: Changing geometry of a deep-drawing die by MIG-welding [9].

Machining in the Aviation Industry

In aircraft construction, every avoided kilogram of weight enables higher payloads, longer ranges and lower fuel consumption [10]. Due to the need for lightweight construction and the avoidance of safety-critical connections, the components are usually manufactured in integral construction, meaning that they are

manufactured from a single block. For this reason, the machining rates of components in the aircraft industry are up to 90 % or more [11]. For example, on a Boeing 787 Dreamliner over 90 metric tons of titanium alloys are processed into components with a total weight of 11 metric tons [12]. For an Airbus A350 door frame made of a titanium alloy, the finished part with a mass of 25 kg is produced from a raw part with a mass of 550 kg [13]. Due to the sometimes very filigree structures of the aircraft components, the materials must have a high strength [14]. Aluminum, nickel-based and titanium alloys are particularly suitable for this purpose. For example, titanium has approximately the same tensile strength as steel at half the density [12] and is therefore suitable for lightweight construction. The effort required to process titanium alloys is considerably more complex than that for steel alloys. The processes are very time-consuming and energy-intensive, which means that the manufacturing costs are ten times higher than for comparable steel alloys [10]. Due to the low modulus of elasticity, the high cutting forces and the low thermal conductivity factor, cutting speeds must be reduced significantly and tool wear is substantially higher [15]. Therefore, the productivity of the cutting process is lower than that of steel alloys due to the smaller metal removal rate [13]. An exemplary use-case of the nickel-based alloys in aviation industry considered in this publication are engine mounts because the alloys provide high strength even at high temperatures [16]. The final geometry of the finished part is weight-saving and thin-walled. The raw part, on the other hand, has a high weight and is block-shaped. Therefore, large machining volumes are required. Since nickel-based alloys such as Alloy 718 are difficult to machine, special tools must be used. The machining process is demanding and only low metal removal rates are possible [16]. This results in a conflict of objectives between the integral construction method, which on the one hand leads to components with higher safety and lower weight, but on the other hand to a higher energy input due to the higher material requirement and larger machining volume. For a structural component made of Alloy 718 with a machining volume of 90 % from a 1 m³ raw part, an energy consumption estimated of 20 300 kWh is required for conventional machining. The same component produced hybrid is estimated at 6 700 kWh. This corresponds to an energy saving of 66 %. In addition to the advantages of hybrid production in terms of resource efficiency due to near-net-shape machining, there are new possibilities for the component design by adding undercuts and cavities, for example.

Systems Technology and Software Chain for Robot-Based Processes

In Figure 5Figure 5: CAD Model of the HMC. the developed robot-supported hybrid manufacturing system can be seen as a CAD setup.

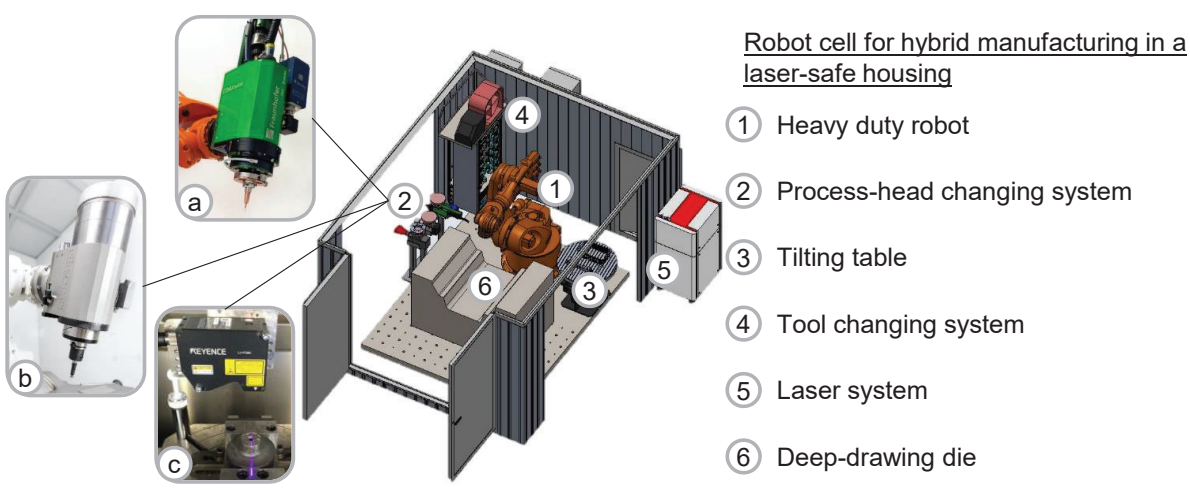

Figure 5: CAD Model of the HMC.

In addition to the robot (1) (KUKA KR500 MT), three end-effectors are implemented in the robot-cell at the process-head changing station (2). These are a wire-based LMD welding head (a), a milling spindle (b) and a 2D

laser line sensor (c) for digitizing the components. (3) is a tilting table for extending the degrees of freedom by two rotary axes. Besides the tool changing system (4), the cell is equipped with a diode laser system (5). At (6), an example component in the form of deep-drawing die can be seen. In the following individual components of the HMC are briefly presented.

The COAXWIRE optic, like it is depicted in Figure 5 (a), is used as the process head for the directed energy deposition welding. Due to its special tri-jet optical system with central wire feed, it enables direction-independent process control as well as high flexibility with regard to the deposition welding position to use in constrained positions [17]. It is powered by a diode laser system (LDF 4000-30) from Laserline GmbH, Figure 5 (5). The use of a laser wire deposition welding system eliminates the need for additional safety precautions and material handling measures, such as those required when using powder. For the machining process a motor spindle from Franz Kessler GmbH, Type SMS 090.32 – 641.138 (similar to the shown in Figure 5 (b)), is used. It is attached to the flange of the industrial robot. The digitization of the additive manufactured components is carried out by means of a laser line scanner [17]. This allows individual profiles of the workpiece to be recorded from different positions in a 2D measurement. The scan is performed using a blue low-energy, linear light beam (Keyence LJ-V7080, Figure 5 (c)), which is guided from different directions at a distance of approximately 80 mm over the surface. The resulting individual images are further processed as a point cloud, and then combined by using an image processing algorithm to form a 3D model. The path planning for the robot-machining is carried out by the CAM tool ROBOTMASTER [18]. Both applications, changing geometries of deep-drawing dies and manufacturing of aircraft parts, are implemented in the previous described HMC. For the combination of the different process steps and ultimately for the realization of the hybrid production chain, a complex process sequence has to be passed through. In Figure 6 the individual work steps in use for digitization are illustrated [17].

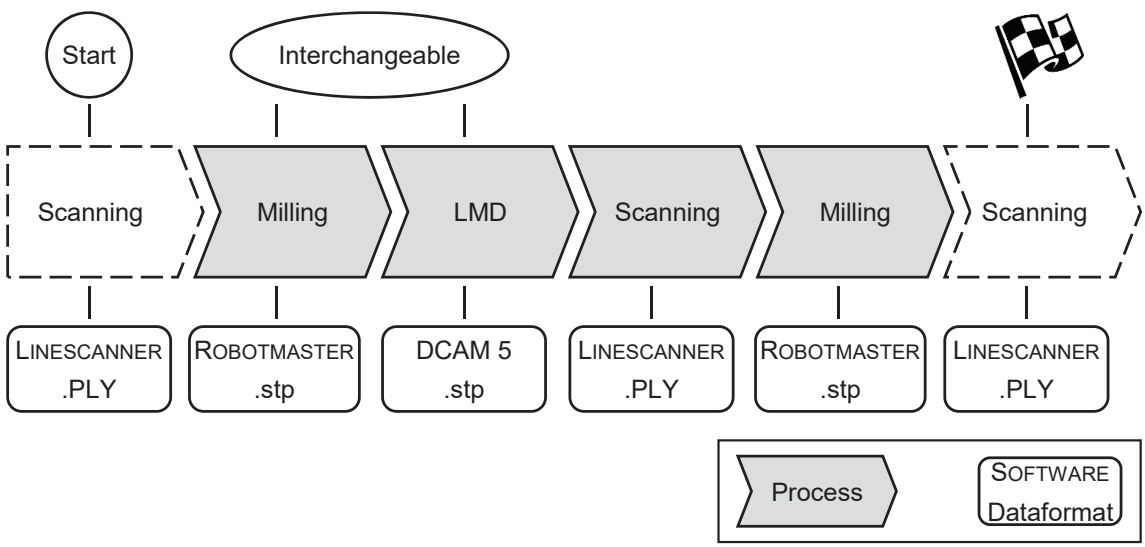

Figure 6: Software chain.

Using standardized data exchange formats such as step, stl and PLY ensures compatibility over a range of proprietary software. The digitization is realized by scanning the workpiece from different directions in the first step. The recorded height sections form a 3D overlapping point cloud. For further processing this cloud is converted into a stl file in order to feed the CAM-program. Due to conversions in the file formats during the scanning process the sequence from left to right is not reversible. Only the modules milling and laser metal deposition (LMD) are interchangeable.

Pretests

Because of the serial axes structure, the robot type used here has significantly poorer static and dynamic characteristics compared to a machine tool [19]. This leads to large displacements of the tool paths as well as in

an increased susceptibility to oscillations during milling, which often results in machine chatter [20, 21]. The design of the axes leads to uneven thermal expansion due to the drives themselves. This has a negative effect on machining accuracy, particularly in the case of asymmetrical axes design [22], which is common in KUKA designs. The challenge is to cope with the low stiffness of the industrial robot and the exact knowledge of the process stability limits [23].

Pretests for Quality-Loops

The reworking of a deep-drawing die usually begins with the milling of a gradated pocket for the insertion of the welded metal of the deposition process. This is then filled by several layers of weld metal, the buffer layers, and finally a top coating, the so-called hard layer. The buffer layers are characterized by a lower hardness, while the hard layer is significantly harder than the base material. This coating interacts with the sheet in the deep-drawing process. The combination of the two layers ensures a crack-free and largely stress-free bond with the base material. After the hard layer has been applied, the deep-drawing die is machined to the final contour. In order to determine the process window for the die finishing, milling tests were carried out on a Fe-based hard coating material developed in the ProGen project. This newly developed material in the form of a flux-cored wire ensures good weldability and bonding with the base material. However, the welded layers can achieve different hardness values due to unfavorable environmental influences, for e.g. contamination and oil films, both of which result in poorer mixing of the alloying elements. For pretests additively manufactured cubes were made from the hard layer material (Durum Progen 6-09), shown in Figure 7 on the right side, to find a suitable process window for producing surfaces with the required roughness of $R_z \leq 12$ µm (minimum requirement from deep-drawing die construction [17]) in the machining process. Their hardness varies between 339 and 661 HV 30 on the raw welded surface. The high fluctuations in the hardness of the material and the modulation of chip thickness cause structural vibrations of the robot. For this reason, the upper surfaces of the workpieces were grounded. This means that the surfaces have a more homogeneous hardness distribution, since influences from the slag of the welding process or from alloying elements hardened in different ways due to uneven cooling can be compensated. The reference material is 1.0038 (ASTM A 252, A500, A501 (US) 100/70/03), which is machined using the same parameters. The depth of cut a_p and the cutting speed v_c were varied during the tests. The milling operation was executed along the positive x-coordinate. As shown in Figure 7, a higher depth of cut with a constant cutting speed leads to an increased cutter displacement at the end of each toolpath. When machining with a robot, this leads to a pretension of the robot arm similar to a spring and creates a spring-back effect of the robot structure at the end of the milling paths when leaving the material.

Figure 7: Influence of depth of cut on surface quality and tool displacement at cutter exit [8].

The roughness values of the milled path were then measured. The effect of variation of these technology parameters on the surface roughness is illustrated in Figure 8. Herein the values which are marked with red circles are measured values whereas the rest is linear interpolated.

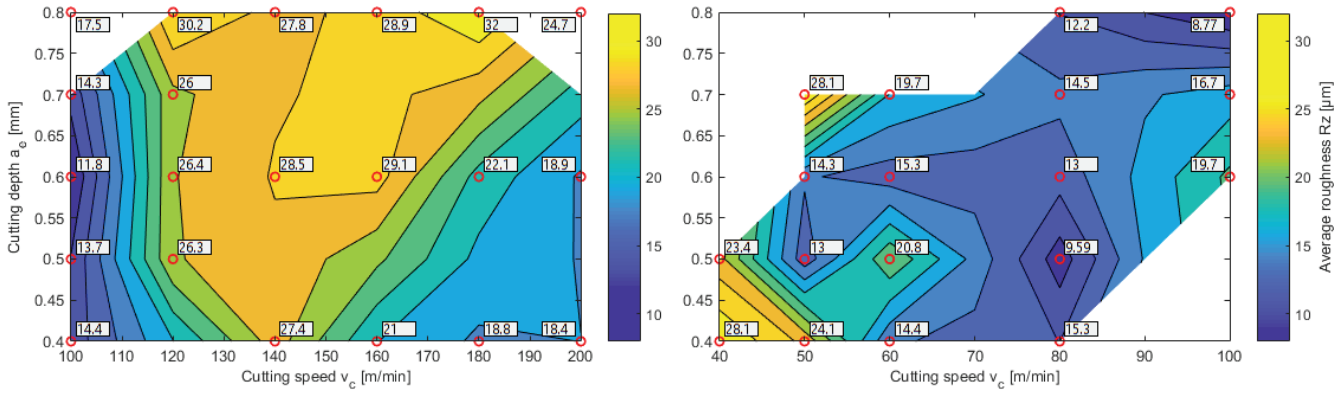

Figure 8: Full slot milling with different cutting speeds and milling depths 1.0038 (left) and Durum Progen 6-09 (right) [8]

As an additional requirement, the varied parameters have been examined for the avoidance of this effect. As a result, the depth of cut a_p was reduced to a minimum between 0.5 and 0.6 mm. The best results for 1.0038 were achieved at a cutting depth of $a_p = 0.6$ mm and a cutting speed of $v_c = 100$ m/min. With regard to the post-processing of the additively produced workpieces, comparable results could be achieved by reducing the cutting speed to 50 % of the reference material. The results for $R_z \leq 12$ µm were achieved at cutting depth of $a_p = 0.5$ mm and cutting speed $v_c = 50$ m/min. The required average roughness depth can be achieved with this technology for both materials, the additive- and the reference material. The values determined were used for pilot tests on a smaller demonstrator, as shown in Figure 9. The demonstrator was developed together with Opel Automobile GmbH and shows two typical deep-drawing die geometries on a compact surface (LW 300 x 300 mm²). This is a free-form surface for an outer skin on the front half, on the right side in Figure 9, and functional surfaces for an inner door surface on the back half. On this demonstrator, conceivable modifications for a deep-drawing die are welded on. These include changes to the free-form surface and change welds on radii for beadings and functional openings, for example loudspeakers or window regulators.

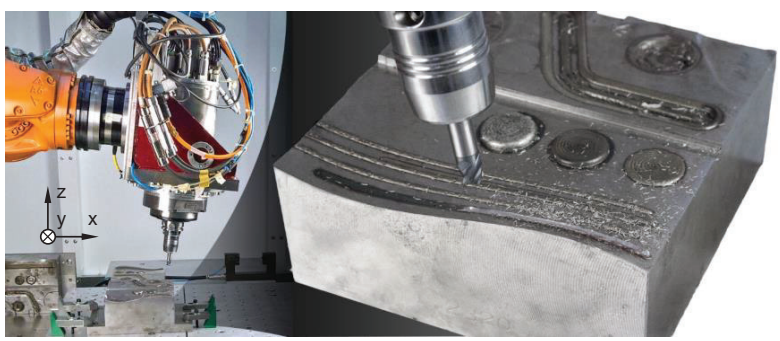

Figure 9: Demonstrating changing a deep-drawing die for quality-loops [24].

In the preliminary tests for this application, the dimensional accuracy of the machined geometries could be increased to (±0.1 mm) by means of an extended path planning strategy [25, 26].

Quality-Loops

Based upon the presented example for the quality-loop, the strategy for a finishing process on a deep-drawing die demonstrator for a trunk flap is shown in Figure 10, (1). A gradated pocket (2) provides the base for the insertion of the buffer layer and the hard layer, which are filled by wire based laser metal deposition afterwards. The gradation improves the connection of the weld metal to the substrate. The height and width of the gradation depends on the filler metal.

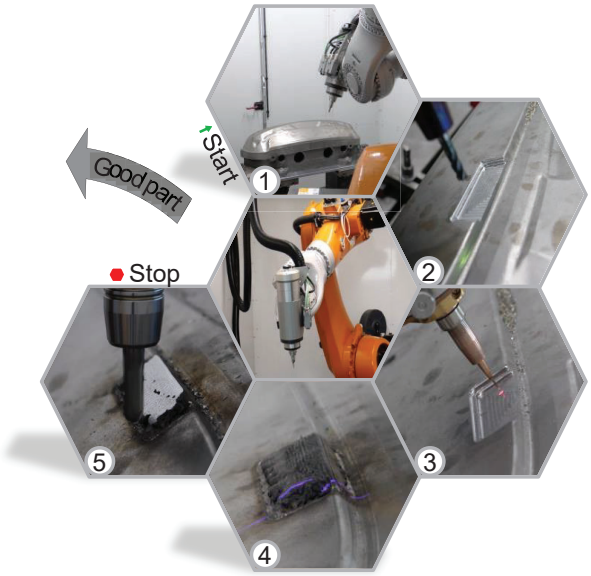

Figure 10: Robot-based quality-loop.

After milling the pocket, the layer structure for the final geometry is created by interchanging the COAXwire process head, see (3). In this case, the buffer layer and the hard layer were welded together without intermediate milling. The subsequent scanning process, shown in 4, enables more accurate path planning for machining post-processing, as is depicted in Figure 10, (5). For the defined finishing process with $R_z \leq 12$ µm, it is only necessary to run the hybrid production chain once. If the geometries become more complex, a repeated run may be necessary in order to achieve the required accuracies.

Aviation Industry

As an application for the aviation industry, an Airbus engine mount is produced using hybrid manufacturing technology. The application is primarily focused on the design of a resource-efficient manufacturing process. The bracket consists of Alloy 718 with the dimensions (LWH) 500 x 65 x 50 mm³.

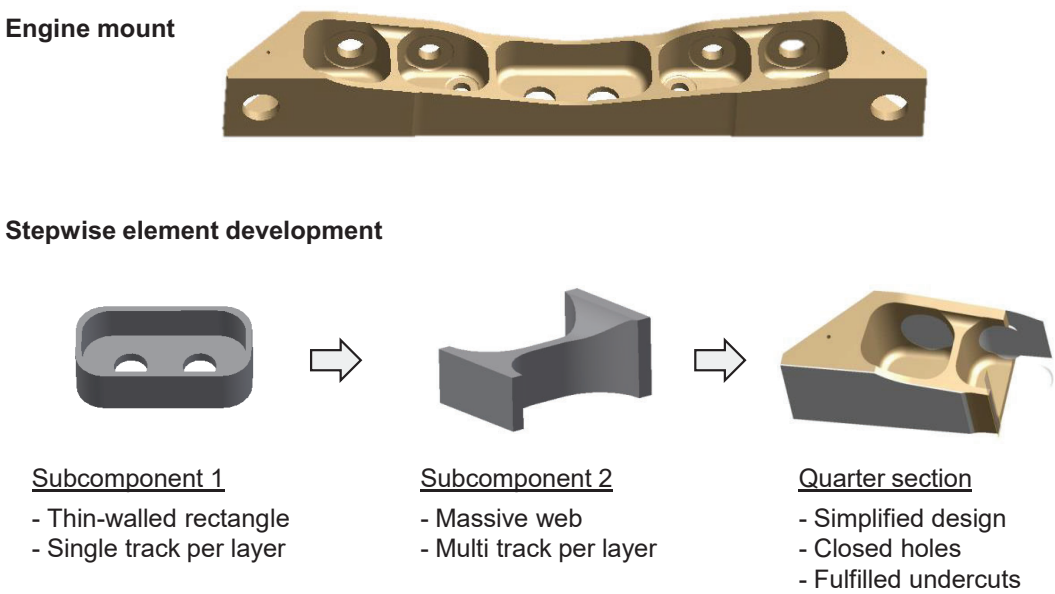

Figure 11: Engine mount development.

In conventional production, this geometry is milled from a solid block with a material removal volume of approx. 79 % [17]. Due to the poor machinability of the material resulting in lower tool life, near-net-shape production results in considerable cost savings by reducing production time and tool expenditure [27]. As shown in Figure 11, the component for the development of the additive process was divided into subcomponents and applied to a simplified geometry in order to provide industrial applicability. The quarter segment has a volume of (LWH) 140 x 55 x 70 mm³ and was additively manufactured in approximately 30 minutes (excluding cooling time) on a substrate made of mild steel. The upper part of this segment is finished using a four-edged milling cutter for Ni-based alloys with the tolerances and parameters shown in Figure 12.

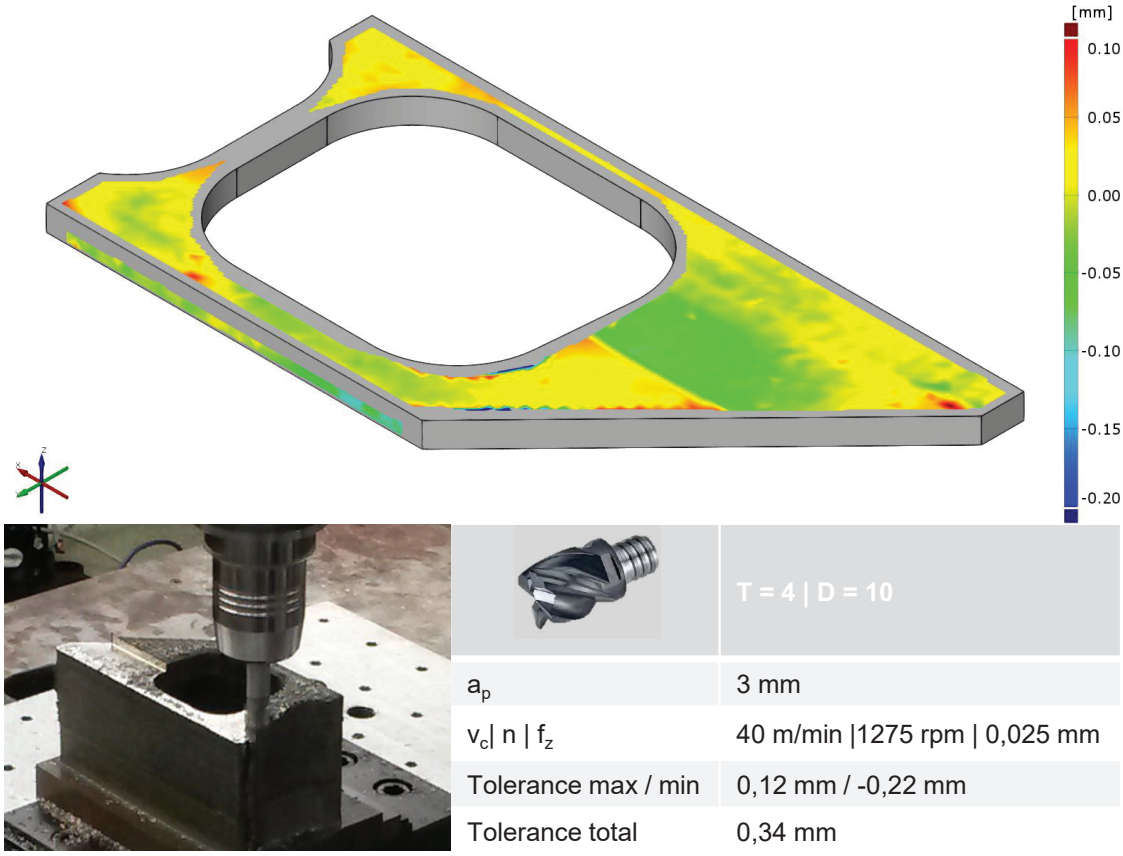

Figure 12: Machining results engine mount made of Alloy 718.

In Figure 12, the machined mount shows a clear difference in the height of the surface on the right-hand side in the longitudinal direction. This deviation is a result due to growth of the robot structure by heat input from the environment [22]. The mount was machined in the PTW laboratory on two different days. The temperature difference was approximately 10°K, while the robot structure was not recalibrated.

Summary and Outlook

This publication shows the realization of a robot-supported hybrid production chain. A wire-based LMD process was chosen as the basis of the hybrid manufacturing concept. It enables simple material handling and allows direction-independent generation of deposition paths via the COAXwire process-head of the Fraunhofer IWS in Dresden, Germany. By linking the process with a 2D laser line scan process and machining post-processing, a robot-based hybrid manufacturing center for resource- and energy-efficient production has been created. Proof of industrial suitability is provided on the basis of two application scenarios. These are the use of the hybrid manufacturing center in the quality-loop in deep-drawing die construction and the processing of nickel-based alloys for the aviation industry. Without the use of additional sensors, the accuracy of robot processing could be increased to a few tenths of a mm (0.1 to 0.2 mm) by means of extended path planning strategies. In the case of deep-drawing die construction such a hybrid manufacturing center expands the machine capacity in the sense of reduction of the machine occupancy for high-precision machine tools that can meet the high tolerance requirements of tool construction. The built robot-cell will be used in the PTW's technical center for future research projects regarding a holistic CAM software for the hybrid process, as well as for new approaches for increasing the absolute accuracy of industrial robots, so that this manufacturing technology can be further expanded and its range of applications extended.

Acknowledgments

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