Lasers in Manufacturing Conference 2017

Performance of hot forging tools built by laser metal deposition of hot work tool steel X37CrMoV5-1

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Abstract

In industry the variety of products is increasing and product life cycles are getting shorter. For parts made by forging processes this trend leads to very high prizes, as the tool costs have to be assimilated with only few parts. To reduce the tool costs new, flexible processes have to be established in tool manufacturing. Laser based additive manufacturing is noted for its high flexibility and especially Laser Metal Deposition (LMD) process, which is already used for coating and repairing of forming tools, would be qualified for the production of forging tools. Within first investigations the hot work tool steel X37CrMoV5-1 (DIN 1.2343) was successfully processed with LMD to generate 3D structures without cracks and a relative density of 99.9%.

In this work an additive manufactured forging tool for a fork joint was designed using the hot work steel X37CrMoV5-1. The tool is a hybrid part with a conventional manufactured base part and a forming element added by LMD. The mechanical properties of additive manufactured specimen are analysed by compression tests and are compared to conventional manufactured specimen. Afterwards the occurring stresses during forging are analysed by a numerical simulation. The designed hybrid tool is manufactured by LMD and finished by machining. Finally the tools are tested under serial production conditions with a workpiece temperature of 900 °C. For quality assurance the produced parts are checked randomly to evaluate the accuracy of the forging process.

Keywords: Tool Manufacturing; Laser Metal Deposition; Additive Manufacturing

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1. Introduction

In industry changeover cycles in production are reduced to offer a large range of customised products to fulfil the individual requirements of the customers [Rastogni 2009]. This affects not only design elements but also highly loaded functional parts made by forging processes. However, forging tools are cost intensive, so individual products that have to be produced by forging get excessively expensive. To realise mass customisation, a more cost efficient way for manufacturing and adapting forging tools is needed.

Due to its high flexibility, laser based additive manufacturing of metal parts is a promising technology for tool manufacturing. A modular tool for press hardening with optimised tempering was be designed and produced by using Laser Beam Melting (LBM) in powder bed [Müller et al. 2014]. Furthermore a hot forging tool with integrated tempering channels was developed and built by LBM [Husik et al. 2012]. Compared to a conventional manufactured tool without active tempering the wear could be significantly reduced in a test of 500 cycles [Husik et al. 2013]. This emphasizes the possibilities and advantages of additive manufacturing. The investigations for tool manufacturing by LBM are mainly conducted with the hot work tool steel X3NiCoMoTi18-9-5 (1.2709) because high carbon tool steel as it is commonly used in tool production cannot be processed by this technology very well. Another laser based additive manufacturing process is the Laser Metal Deposition (LMD). This process is already used to repair or coat forging tools by adding new material at worn out sections and subsequent machining to receive a smooth surface [Eimann et al. 2000]. The main advantage of LMD is the possibility to generate three dimensional structures on freeform surfaces [Toysercani et al. 2005]. That leads to the idea to generate hybrid tools, which combine a geometrically simple base part with active parts built by additive manufacturing. In order to realise resilient forging tools, the processing of high carbon hot work tool steel as X37CrMoV5-1 (1.2343) is necessary.

First investigations showed the possibility of building three dimensional structures without cracks and almost no pores with this steel. As active parts of a tool will be added onto a machined base part, the bonding of the additive manufactured part to the substrate was analysed. Within that investigation it has been proofed that the bonding of an additive manufactured part onto the substrate does not weaken the hybrid part [Junker et al 2016].

In the actual work the performance of a hybrid tool will be investigated. First the tool is designed by numerical analysis and the strength of additive manufactured tool steel is measured. The active element of the forging tool is manufactured with LMD and the tool is finished by machining. After the forging tests the wear is analysed.

2. Tool design and performance test

First compression tests are conducted to analyse mechanical properties of additive manufactured hot work tool steel X37CrMoV5-1. Using a numerical simulation the stresses occurring during forging are identified and compared with the investigated mechanical properties. By taking the yield strength and the geometrical accuracy into consideration a parameter set is chosen to build hybrid forging tools as shown in Fig. 1. The tools are tested in an industrial forging process under serial production conditions. In the end the tool performance is evaluated by a wear analysis.

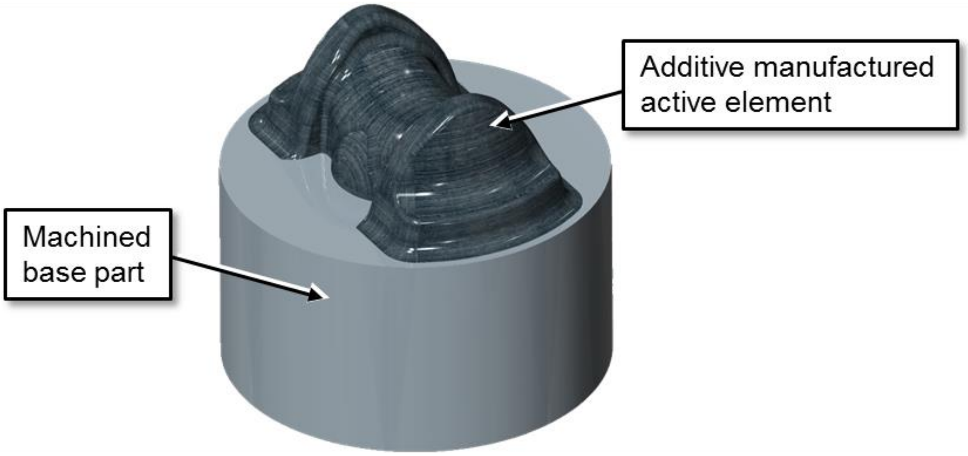

Fig. 1. Principle of the hybrid tool with a machined base part and an active element added by additive manufacturing with LMD

2.1. Mechanical characterisation

As the main load of the active element of the tested tool during forging is of compression stress the mechanical properties of additive manufactured tool steel X37CrMoV5-1 are analysed by compression testing. The tests are conducted at the Institute of Manufacturing Technology according to DIN 50106 [DIN 50106 1978] with a universal testing machine. The tests are executed with compression velocity of 5 mm/min and the specimens are compressed to 35 % of the initial height. Because of the high load during compression testing a carbide flat die is used. For constant low friction conditions teflon sheets were put between the specimen and the flat dies.

For the analysis of the mechanical properties of additive manufactured tool steel, two test setups of LMD parameters are investigated. One set with a laser power of 600 W and a feed rate of 600 mm/min and the other set with a laser power of 900 W and a feed rate of 800 mm/min. All other parameters like powder mass flow, spot diameter and inert gas flow were held constant. The specimens for compression testing, with a diameter of 6 mm and a height of 9 mm, are machined out of additive manufactured cubes with an edge length of 15 mm. To achieve the requested strength the specimens are heat treated, with an austenitisation at about 1010°C and three times annealing at about 560°C, like it is performed in conventional tool manufacturing. The Laser Metal Deposition is conducted at the Institute of Photonic Technologies on a laser metal deposition machine TLC3008 from the company Trumpf GmbH. To qualify the mechanical properties the results are compared to those of bulk material of the hot work tool steel X37CrMoV5-1.

The characterisation is occurred by the Yield Strength at 0.2 % forming. Comparing the results, shown in Fig. 2, it can be analysed that the materials properties of additive manufactured specimens under compression stress are in the same range like those of bulk material reference which has a Yield Strength of 1652 MPa ±3.7 MPa. The stress of the additive manufactured material with 600 W and 600 mm/min feed rate has a strength of 1644 MPa ±8.2 MPa. The material manufactured with laser power of 900 W and a feed rate of 800 mm/min has a strength of 1640 MPa ±5.1 MPa. After the heat treatment that is commonly used in tool production the parameters of the LMD process do not affect the materials strength.

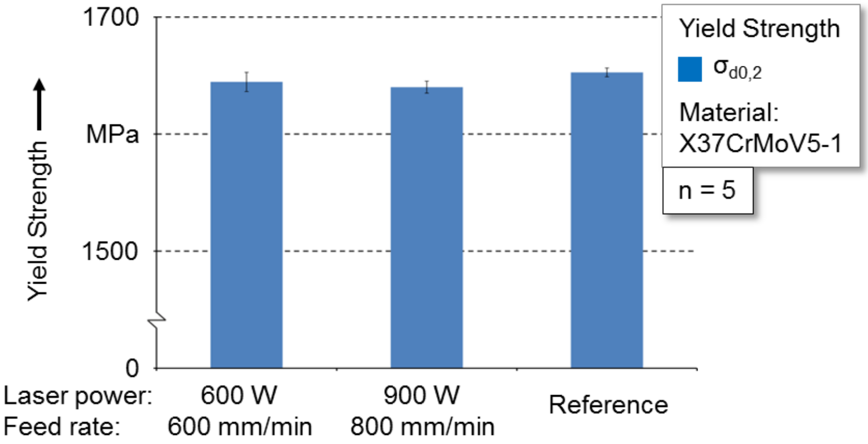

Fig. 2. Comparison of compression stress at 0.2 % forming of additive manufactured hot work tool steel X37CrMoV5-1 and a reference bulk material of the same steel

2.2. Numerical tool design

For numerical tool design the software simufact.forming 12.0.1 is used. As workpiece a preformed semi-finished product is used and meshed with hexagonal elements with an edge length of 1 mm. As material a commonly used forming steel 16MnCr5 is used at a temperature of 900°C. To identify the tool load the tool is implemented deformable and is meshed with tetrahedral elements. As material a pre implemented file of the tool steel X37CrMoV5-1 is used. For friction a friction factor of m = 0.15 is applied and the forming speed of the press is set to 200 mm/s but since no strain-rate dependents is implemented to the material the forming speed dos not affect the calculated forces.

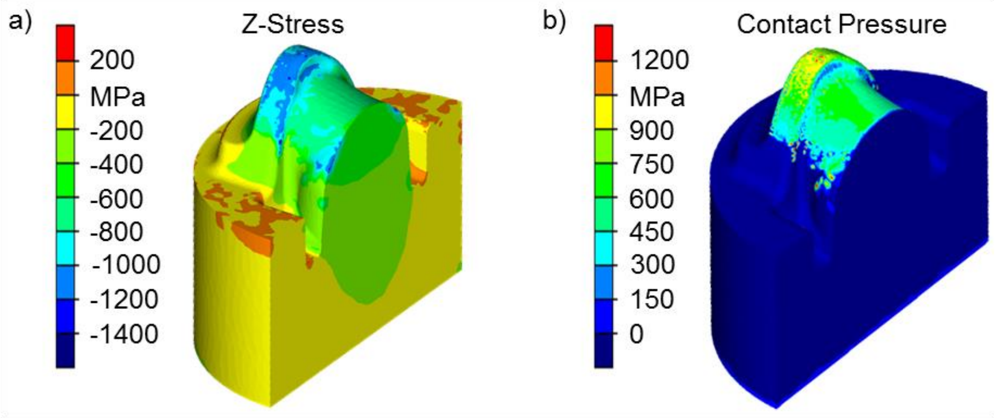

Fig. 3. Numerical analysis of a) stress in z-direction and b) contact pressure of the forging tool

Analysing the stress in z-direction, which is the main loading direction, shown in Fig. 3 a), it can be identified that the active element is mainly loaded by compression stress. The highest stress occurs on the shoulder where the material flow is hindered in order to regulate the flow direction. The compression stress reaches a maximum of about 1200 MPa. Tensile stresses only result in the lower part of the tool that will be produced by machining.

Analysing the contact pressure, depicted in Fig. 3 b), the same result is shown, that the main load is at the tool shoulder with contact pressure up to 1200 MPa. Summarizing the results of the numerical investigations the tool material should resist a compression load of at least 1200 MPa.

Regarding the mechanical properties of additive manufactured tool steel X37CrMoV5-1 the requirements of compression strength higher than 1200 MPa are fulfilled for both tested parameter sets. To receive an economical production chain for hybrid tool manufacturing the geometrical accuracy is important to produce a near net shape part and minimise subsequent machining. High laser power during LMD results in a high heat input and therefore a bigger melt pool. This leads to collapsing edges and larger errors at a high amount of layers and thus the geometrical accuracy decreases, especially for larger parts. As the parameters of 600 W laser power and a feed rate of 600 mm/min had shown a higher geometrical accuracy these parameters are chosen for the production of a forging tool that is tested in a serial forging process.

2.3. Tool production with LMD and machining

After analysing the mechanical properties of the additive manufactured material, analysing the occurring forces during forging and selecting the most suitable laser parameters, the CAD-File is enlarged for about 0.3 mm on each side to get an offset for a subsequent machining and sliced into several layers. The layer height, the number of layers as well as the geometrical accuracy depends on the laser parameters. The selected parameters are a laser power of 600 W and a feed rate of 600 mm/min which had shown a good geometrical accuracy. Using these parameters about 56 layers are needed to produce the active element of the forging tool.

The hybrid tool manufactured by adding the active element by LMD on a machined base part is shown in Fig. 4 a). Although the volume of the produced active element is much higher than that of the test structures used for the parameter identification the geometrical accuracy and the bonding to the base part do not show visual defects after the additive manufacturing.

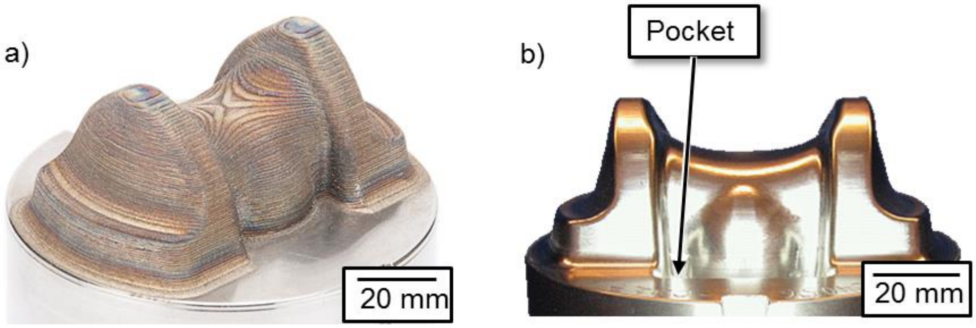

Fig. 4. a) Hybrid tool with machined base body and additive manufactured active element and b) hybrid tool after machining

The tool includes a pocket on each side, shown in Fig. 4 b), to produce the geometry of the fork. As these pockets are manufactured more economical by milling the hybrid tool has to be machined after the additive manufacturing of the active element. Thus the rough surface after the LMD and the enlargement of 0.3 mm do not negatively affect the production chain. Within former investigations it was analysed that the high cooling rate during the laser based additive manufacturing cause a very high hardness of the built part. Due to this the heat treatment is conducted before machining.

At the finished tool defects are visible which were uncovered during the machining. On the one side a pore that can be caused by instabilities of the additive process got uncovered, shown in Fig. 5 b). As in-situ process control is still investigated in several scientific works, instabilities during LMD cannot be compensated consequently that can lead to few defects inside the manufactured part. By machining the final geometry such defects can get uncovered on the tool surface. Analysing the surface of the manufactured tool only one pore was detected so a very low porosity of the tool can be assumed.

Furthermore hairline cracks at the bonding area of the additive manufactured tool element and the machined base part are exposed, shown in Fig. 5 a). These cracks can be caused by thermal tensions resulting from the melting during the laser additive manufacturing process. In former investigations the tool steel X37CrMoV5-1 was processed without preheating of the substrate, as the heat induced by LMD heated up the substrate during the process, therefore the thermal gradient got small and the internal stresses were in a moderate range.

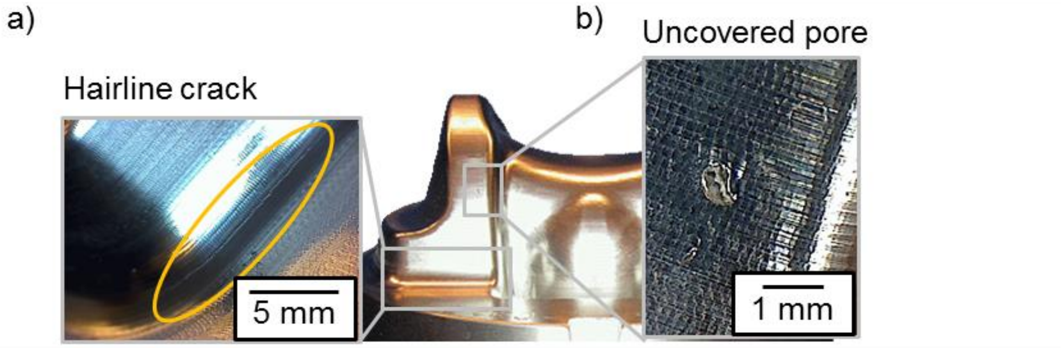

Fig. 5. Uncovered defects after surface machining: a) hairline crack at the bonding area of the additive manufactured active element and the machined base body and b) uncovered pore at the tools shoulder

The hybrid tool production was conducted with a not preheated base part as well but both, the volume of the base part as well as the volume of the additive added element were a lot bigger than in the pretests, therefore the thermal gradient and the internal stresses are assumed to be much higher and could cause the hairline cracks at the bonding area. During forging theses defects could cause an early failure of the tool as the cracks can grow due to alternating stresses.

2.4. Forging tests in serial production conditions

The hybrid manufactured tool is integrated to a serial production process at the Hirschvogel Umformtechnik GmbH. The tested hybrid tool is used in one forming station in the production of a fork for a fork joint.

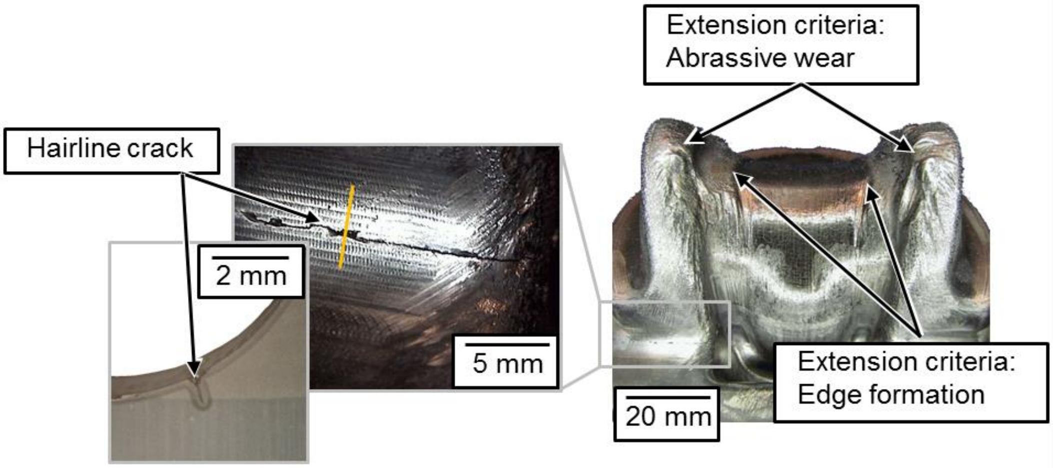

Fig. 6. Analysis of the hairline crack after forging by an enlargement and a cross section.

Mainly tensile stresses will cause the growth of the cracks but as the analysis of the simulation had shown that at the area where the cracks are arisen, primarily compression stresses will occur during forging. For that reason the forging test are conducted even though the cracks already exist in the tool.

As expected the tool did not break during forging. After a life time of about 50% of the tool used in serial production the hybrid tool has to be changed due to edge formation in the upper part of the active element where the bulk material hits the tool first at each stroke, shown in Fig. 6, and abrasive wear at the tools shoulders. That equals the extension criteria of tools used in serial production. As the serial tools material is different further investigations with machined tools are in progress to qualify the hybrid tools life time.

Analysing the cracks after forging it can be observed that they slightly burst at the surface. Examining a cross section the depth of the crack can be measured with about 400 µm and it can be seen that it ends at the bonding edge between bulk base part and additive manufactured active element. As presumed the crack arises few layers above the bonding layer to the substrate. That is due to the relatively sharp edge between the flat base part and the additive built active element. As mentioned before, the thermal gradient caused by the heat input during the laser process leads to high internal stresses. Sharp edges and big differences of the parts cross sections can cause increased stress that leads to fracture inside the part. To avoid cracks at the bonding area further investigations will be made with preheated base parts and a radius to the active element.

3. Summary and outlook

To increase flexibility in tool production laser metal deposition of high carbon hot work tool steel is investigated. An analysis of the mechanical properties shows that after a conventional heat treatment for tools additive manufactured tool steel X37CrMoV5-1 has the same yield strength like bulk material of this steel. Furthermore the used parameters do not affect the strength of the material. To design a forging tool producing a fork joint the occurring forces during forging are analysed by a numerical simulation. As the main load is characterised by compression stresses the mechanical properties of the used additive manufactured hot work tool steel X37CrMoV5-1 are investigated by compression testing. The results of the test had shown that after a conventional heat treatment the strength of additive manufactured material fulfils the requirements to be used for the forging tool. Although an additive manufactured tool had hairline cracks at the bonding area between the bulk base body and the additive added active element, it was successfully used in a serial forging process. The hybrid tool was changed due to high wear at the active element. That is the same extension criteria as it is for conventionally used forging tools.

Within further investigations the bulk base body will be preheated to avoid hairline cracks at the bonding area. Furthermore forging test will be conducted with conventional machined tools of the hot work tool steel X37CrMoV5-1 to qualify the life time of a hybrid tool compared to a conventional manufactured tool.

Acknowledgements

The work presented in the paper was kindly founded by the Bavarian Research Foundation (BFS) in the course of the Research Association “ForNextGen - Next Generation Tools”.

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