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Procedia CIRP 111 (2022) 210–213

www.elsevier.com/locate/procedia

12th CIRP Conference on Photonic Technologies [LANE 2022], 4-8 September 2022, Fürth, Germany

Laser Metal Deposition of AlSi10Mg with high build rates

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Abstract

Additive manufacturing with aluminum alloys is becoming increasingly important in the automotive industry to meet the growing demand for lightweight construction and flexibility. However, higher build rates and higher process efficiency are necessary for laser metal deposition (LMD) to be more economically competitive. The so called high-speed LMD allows high build rates by partial melting of the powder before it hits the melt pool but is currently limited to coatings of rotationally symmetrical parts. Our goal is to apply this process technology to the additive manufacturing of AlSi10Mg and thereby increase the build rate.

In this work we demonstrate a successful build-up of cuboids manufactured with the alloy AlSi10Mg using feed rates ten times higher compared to state of the art. The tensile strength of these cuboids is in the range of 180 to 220 MPa.

Keywords: laser metal deposition, high-speed LMD, additive manufacturing, aluminum alloy

1. Introduction

The manufacturing industry and especially the automotive sector face the challenge of short development and product life cycles, increasing variety and the demand for CO_2 savings [1,2,3]. For these challenges and the associated trend towards lightweight construction, additive manufacturing of aluminum alloys shows a high potential. Aluminum alloys are already indispensable in the automotive industry and a further increase of the aluminum content in vehicles, especially for car body and chassis, is expected [4, 5].

One way to meet the demand for flexibility and cost-effectiveness is to use a forged or cast series component and reinforce it or integrate an additional function with Laser Metal Deposition (LMD) as required without a separate mold. These two aspects were investigated in the public founded FlexCar project using the example of a control arm. The series component of the Mercedes B-Class was upgraded for the load cases of the rolling chassis and extended by an additional damper connection. This entails several requirements for the additive structures: For economic reasons, the feed rate should be as high as possible, and the mechanical requirements of the automotive industry must be met.

LMD represents a flexible additive manufacturing technology where a three-dimensional part can be formed by depositing multiple welding tracks side by side. To form these welding tracks, powder material is coaxially injected into a directed laser beam. The laser beam melts both powder additive and substrate, creating a melt pool in which the deposited powder metallurgically bonds with the base material [6–9].

The demand for high feed rates can be met with High-Speed LMD. In this process high feed rates up to 100-200 m/min can be reached by partially melting the powder before it hits the melt pool [10–12]. However, this process is currently limited to coatings of rotationally symmetric components.

10.1016/j.procir.2022.08.050

Additive manufacturing of LMD with AlSi10Mg for non-rotationally symmetrical components and its mechanical properties have been investigated by several studies [13–18] up to a feed rate of 1 m/min. The tensile strength varies strongly between these studies. Chen et al [13] reached tensile strength of 165 MPa, while Wang et al. [18] reached tensile strength up to 360 MPa. Further increase in tensile strength can be achieved by heat treatment of the finished part [15, 16].

The goal of our work is to build additive structures of AlSi10Mg with highest possible build rates, that meet the mechanical requirements of the automotive sector. This represents an extension of the state of the art, which is currently limited to feed rates of < 1 m/min.

2. Experimental procedure

2.1. Materials & equipment

The experiments were carried out on the TruLaserCell3000 machine with a 4 kW disk laser, a laser light cable with a diameter of 100 µm, the *focusLine Professional* optics, and a LMD MultiJet nozzle from *TRUMPF Laser- und Systemtechnik GmbH.* The experiments were conducted with a defocused laser beam with a focus diameter of 200µm and a beam diameter of 2 mm on the surface of the substrat. The powder of AlSi10Mg with a distribution of the particle diameters ranging from 45 to 107 µm was conveyed to the process zone by means of a vibratory feeder from *Medicoat AG* and a helium gas flow. Argon was used as a shield gas to protect the process from surrounding atmosphere.

2.2. Single welding tracks

In a first step, the parameters were explored by welding single tracks on a 10 mm thick plate of AlMg3 with variable feed rate between 1 and 20 m/min and variable laser power ranging from 1600 W to 4000 W as seen in Fig. 2. The powder feed rate was adjusted in a way that mass per distance was 2.1 g/m for all parameters. The welding tracks were cut perpendicular to the feed direction, ground, polished and etched with water solution containing 10% of sodium hydroxide. The resulting cross-sections were evaluated using a light microscope as exemplified in Fig. 1. The depth *t*, the width *b* and the height *h* of the track were measured. The aspect ratio *AR* is calculated as follows

$$AR = \frac{b}{h} \tag{1}$$

and the dilution *D* is calculated by

$$D = \frac{t}{t+h} \tag{2}$$

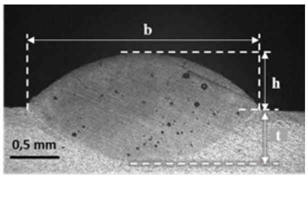

Fig. 1. Microscopical image of a single welding track

We defined the following three criteria for a welding track to be suitable for volume build-ups:

- A welding track is regarded as suitable if it is continuous and the powder is completely melted.
- Aspect ratios less than 3.6 can lead to cavities between adjacent welding tracks. In literature welding tracks between 3.6 and 5 are regarded as suitable for additive manufacturing [19–21]
- The dilution *D* should be as small as possible. If the first two criteria are fulfilled, the track with lower dilution is preferred.

2.3. Volume build-up

In a second step, we additively manufactured volume build-ups and determined the mechanical properties with tensile tests according to DIN EN ISO 6892-1:2019 (testing velocity according to mode B) were performed on a *Zwick Typ 250kN Allround RED*. Laser power and feed rate were varied within a factorial design of experiments (DoE) with the values in Table 1. All samples were manufactured with a powder feed rate of 18.3 g/min, a laser beam diameter of 2 mm on the surface of the substrate, a shielding gas rate of 11 l/min, a transport gas rate of 8 l/min, a track offset of 0.8 mm and a layer height of 0.73 mm. Each parameter combination was repeated three times.

Table 1. Parameters for volume build-up

	Step -1	Step0	Step 1
Laser Power	2800 W	3200 W	3600 W
Feed rate	8 m/min	9 m/min	10 m/min

Tensile specimens according to DIN 50125-E4×10×120 were gained from the cuboids in layer orientation by cutting and grinding. Thiele [15] measured a decrease in tensile strength of 6 % when the tensile specimens are taken perpendicular to the layer orientation. The difference in tensile strength for different orientations is neglected and only tensile strength for in-plane orientation is investigated.

3. Results

3.1. Parameter exploration by welding single tracks

Fig. 2 shows the evaluation of the single welding tracks. The first point represents the evaluation of the bonding to the substrat, with the the second point we evaluate whether the desired aspect ratio is achieved and the third point represents how the dilution is evaluated. These three criteria are rated green, orange and red according to the legend in Fig. 2. Up to a feed rate of 10 m/min, parameter combinations can be identified that fullfil all the defined criteria (circled). With a maximum laser power of 4 kW and feed rates above 10 m/min the width of the weld tracks become smaller; therefore a desired AR of >3.6 can not be achieved.

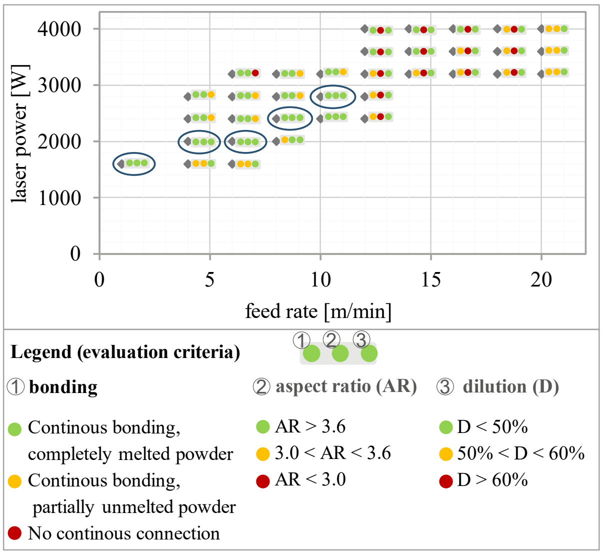

Fig. 2. Evaluation of single welding tracks with feed rate up to 20 m/min

Fig. 3 shows exemplary microscopical images of three single tracks welded at different feed rate. The left picture of Fig. 3 shows a single welding track produced at a feed rate of 8 m/min and the picture in the middle one produced at 10 m/min. These two welding tracks meet all defined criteria. The right side of Fig. 3 shows a single track produced at a feed rate of 14 m/min where the aspect ratio is below 3 and therefore not suitable for additive build-ups. The tracks manufactured at feed rates higher than 10 m/min are narrower because the powder is not completely melted in the edge areas of the track and cannot contribute to an effective build-up.

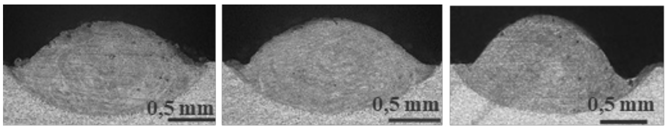

Fig. 3. Example of three single welding tracks: feed rate of 8 m/min and laser power of 2,4 kW on the left, 10 m/min and 3,2 kW in the middle and 14 m/min and 4 kW on the right

3.2. Volume build-up

The mechanical properties were determined using volume build-ups. The ultimate tensile strength (UTS) and the elongation at break ε are shown in Fig. 4.

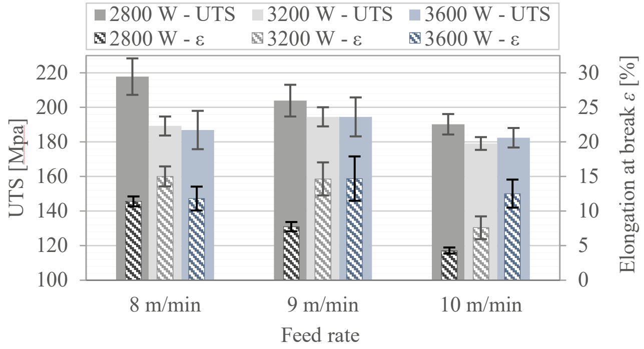

Fig. 4. Ultimate tensile strength (UTS) and elongation (hatched) for different feed rates and different levels of laser power.

The highest tensile strength is achieved at a feed rate of 8 m/min and a laser power of 2800 W. The ultimate tensile strength (UTS) decreases when the laser power is increased to 3200 W and remains at the same level when the laser power is further increased to 3600 W. This trend can also be observed when welding at a feed rate of 9 m/min and 10 m/min. For a laser power of 2800 W, the figure reveals a monotonous decrease in UTS when the speed is increased to 10 m/min. No clear trend is observable for the investigated laser power of 3200 W and 3600 W when increasing the feed rate.

The measured elongation ranges between 4% when welding at a laser power of 2800 W and a feed rate of 10 m/min up to 15% when welding at a feed rate of 8 m/min and 3200 W. When welding at a feed rate of 10 m/min, the elongation at break increases monotonously from 4% to 13% when the laser power is increased from 2800 W to 3600 W.

The root cause of these results needs further investigation, but our preliminary explanation is as follows: When using higher laser powers of 3200 W and 3600 W, the build-up material remains at higher temperatures during the entire process in comparison to lower laser powers. These higher temperatures could potentially lead to an annealing effect, which can explain lower UTS and higher elongation in comparison to lower laser powers.

3.3. Exemplary component

One possible application of such build-ups is the modification of series components with LMD. In this work, we modified the series production control arm of the Mercedes B-Class, made of a forged AlMgSiCu alloy, to adapt it to the load case in the FlexCAR. The fact that the damper connection in the FlexCar is located directly on the control arm means that the load case differs significantly from the series environment, resulting in very high loads within the component. LMD is used to additively manufacture a functional build-up for the damper connection as well as ribs and patches for the structural reinforcement of the control arm. A simulation with the finite element method (FEM) shows the stresses occurring in the component when applying the FlexCAR load case. Fig. 5 shows the simulation results for the original control arm on the left and the control arm modified with LMD on the right.

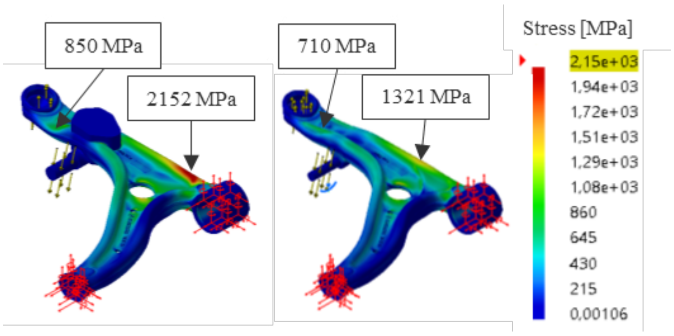

Fig. 5. FEM simulation for stress of the control arm when using the series component (left) and with LMD reinforcements (right)

The mechanical properties for the material applied by LMD were gained from the previously described experiments with a feed rate of 8 m/min and a laser power of 2800 W. The simulation shows that the applied reinforcements can reduce the maximum stress by about 40% (from 2152 MPa to 1321 MPa) compared to the original series component. As a prove of concept the LMD build-ups were manufactured with feed rates of 1 m/min. Welding at higher feed rate has led to unwanted accumulations of applied material in some places due to insufficient acceleration of the machine axes, resulting in a defective build-up. Further investigations must be carried out to manufacture this geometry with significantly higher feed rates.

4. Discussion

This study has demonstrated the potential and the limits of LMD with increased build rates for additive manufacturing of aluminum components. Hereby, the mechanical strength of the manufactured parts reached 220 MPa. This is higher than typical values for casted aluminum parts made of AlSi10Mg (without heat treatment) [22] but cannot compete with the mechanical strength of forged aluminum components. Since the load case for the control arm in the FlexCAR is fundamentally different from the series, the stress exceeds the acceptable values even with the applied reinforcements. Nevertheless, we have shown that a strong stress reduction is possible with LMD. If a component is to be used in a similar way, but with slightly different load cases, it is an attractive option to design a lightweight-optimized component for the lowest load case and modify the component with LMD for higher load cases if required. Furthermore, functional build-ups like brackets can be applied as required with LMD.

So far, we only manufactured simple geometries like cuboids with high feed rates in the range of 8-10 m/min. Geometries like the reinforcements of the control arm could only be manufactured with lower feed rates in the order of magnitude of 1 m/min. To also manufacture these geometries with high feed rates toolpath planning must be optimized considering maximum acceleration and coordination between the machine axes.

5. Summary & Outlook

This study represents the first work in which build-ups of AlSi10Mg with feed rates up to 10 m/min have been successfully manufactured with LMD. Tensile strengths up to 220 MPa were achieved. Further microstructure analyses should explain the observed differences in mechanical strength and help to further optimize the components.

However, manufacturing with such high feed rates is currently limited to simple geometries. To manufacture complex three-dimensional parts, toolpath planning must be optimized considering maximum acceleration and coordination between the axes.

Acknowledgements

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the framework concept “Forschungscampus” ARENA2036 (funding number: 02P18Q643). We would like to take this opportunity to thank all the research and industry partners involved in the FlexCar project.

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