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Additive Manufacturing of a deep drawing tool by direct laser deposition

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Abstract

An additive manufacturing process generating a deep drawing tool by direct laser deposition is described in this paper. Aluminum bronze with ten percent of aluminum content was used as a tool material. Different welding techniques were tested for manufacturing the geometry of the tool. A procedure for examining the welding technique and parameters was demonstrated. Hardness distribution on the cross section of the generated punch was investigated. The results demonstrate the feasibility of the additive manufacturing process using aluminum bronze as tool material, direct laser deposition and a 3-axis-CNC-machining to realize the shape. Subsequently the printed deep drawing tool was successfully applied to form circular cups with an inner diameter of 30 mm made of 1.4301 high alloy steel. On the hand the deep drawing process was carried out by using lubricant and on the other hand cups were formed in a lubricant-free dry metal forming process.

Keywords: additive manufacturing, aluminum bronze, direct laser deposition, dry metal forming, deep drawing

1 Introduction

The first scientific investigation on aluminum bronze was documented 1856 in France. By alloying copper with aluminum the hardness increased and the malleability was not impaired [1]. Nowadays this copper alloy is utilized for several industrial solutions for example for high performance marine engineering applications [2] or deep drawing tools [3]. In automotive and aerospace applications it is also used as a coating material. Investigations of laser cladded aluminum bronze were carried out on mild carbon steel [4] or on AlSi alloy [5].

Direct laser deposition allows to generate industrial products or to modify them. The characteristic feature of this process is the highly localized heat input compared to conventional welding processes which lead to high cooling rates and small heat affected zones. On the one hand it is industrial production process for coatings. On the other hand it is used for maintenance, repair and overhaul (MRO) technologies [6], for example for reconditioning of crankshafts [7]. Different nomenclatures are used for the different applications. For coating processes it is called laser cladding or laser deposition welding. In case of injecting hard particles into the substrate surface it is named laser dispersion or laser injection melting. For MRO technologies or additive manufacturing, often used names are direct laser deposition, direct laser metal deposition, laser engineered net shaping or direct powder deposition.

In the field of additive manufacturing, direct laser deposition is becoming increasingly important and a lot of research and development work have been carried out to enable the implementation of this technology for industrial mass production. This innovative manufacturing process is ideally suited for the generation of near net shape components from which complex finished parts can be machined. Investigations using direct laser deposition were carried out using for example inconel 625 superalloy [8], stellite 21 [9], tool steel [10] or high austenitic steel [11]. Studies in additive manufacturing by direct laser deposition and using aluminum bronze as material have not been reported out yet.

In the conventional deep drawing process lubricant is used because of its positive effects on friction, wear and corrosion behavior [12]. The disadvantage is the negative ecological [13] and economic impact. That is why it is a profitable challenge to decrease the application of lubricant. To this day dry metal forming has not applied for mass production. The vision is to avoid any cleaning

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necessity after the forming process for further production processes like joining or coating. [14]

2 Experimental details

2.1 Materials

The material investigated was a copper alloy named CW305G with the chemical composition of CuAl10Fe1. Gas atomized powder with a particle size from 45 µm to 125 µm was used. Aluminum bronze CW307G with the chemical composition of CuAl10Ni5Fe4 acted as substrate material. Fig. 1 is showing a sketch of the deep drawing tool set and the formed cup. Bores and fits were milled into the substrate for positioning the substrate for direct metal deposition, for post-process milling and for deep drawing. The blank holder, the drawing die and the punch were the components which were generated by direct laser deposition. High alloy steel 1.4301 was used as a sheet material for deep drawing experiments to form the cups. Sheet thickness was 0.5 mm.

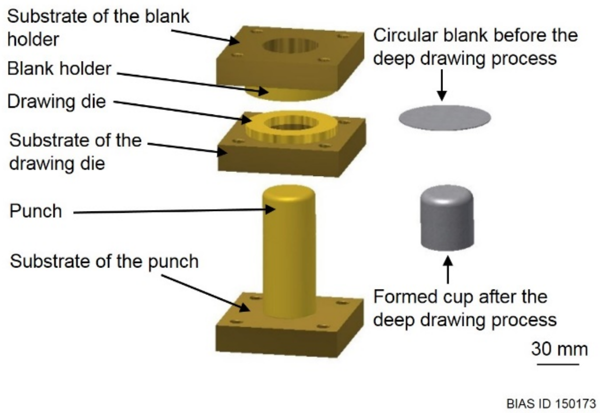

Fig. 1: Sketches of the deep drawing tool and the formed cup

2.2 Additive manufacturing process

The experimental set-up included a 4 kW Trumpf HL4006D lamped pump Nd:YAG laser. A fiber optic cable with a diameter of 600 µm was used to transmit radiation to the Precitec YC50 cladding head where the laser beam was collimated and focused. The head was tilted by 8° to protect the laser head against heating, as commonly applied by prior investigations [15]. The heating was caused by low absorption or high reflection of the copper alloy when using 1064 nm wave length. The laser was focused 10 mm above the substrate surface. The laser processing head was adjusted to receive a spot diameter of 2.5 mm. Argon shielding gas was provided in the center with 16 l/min and also coaxial with 8 l/min. The pneumatic powder feeder GTV MF-PF-2/2 was integrated in the system to feed the cladding powder into the process zone by using 7.5 l/min argon gas. To realize the trajectory for the additive manufacturing process a 3-axis-CNC-machine was used and controlled by G-Code. A turntable machine enabled the rotational movement of the substrate.

Fig. 2 is showing the experimental setup to examine the welding technique and parameters. In the first step the parameters for cladding one track were determined (1). Quality criteria were a good bonding to the substrate, low dilution and a minimum height of approximately 1 mm. The overview of the parameter variation is given in Tab. 1. Mass amount per unit length is a ratio of powder feed rate and welding speed. Energy per unit length is calculated by dividing laser power by speed.

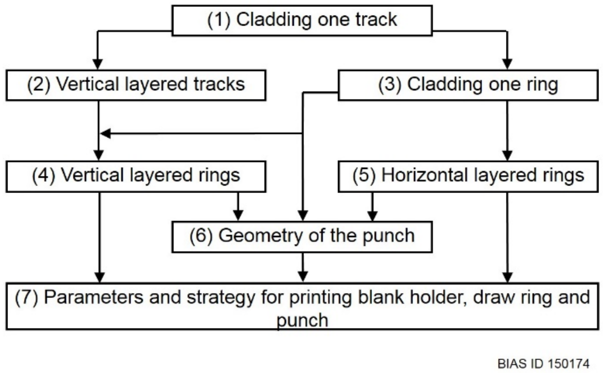

Fig. 2: Process flow diagram of the procedure to examine the welding strategy and parameters for the additive manufacturing process

Tab. 1: Parameter variation

Variation	Laser power [kw]	Speed [mm/min]	Powder feed rate [g/min]	Mass amount per unit length [g/m]	Energy per unit length [J/mm]
Laser power	4 3 2 1	500	20	40	480 360 240 120
speed	4	1000 500 250 150	20	20 40 80 133	480
Powder feed rate	4	500	20 15 10 5	40 30 20 10	480

The parameters thus established were used to generate vertical arranged tracks (2). The aim was to determine the influence of the overlap (z-increment) for generating a multilayer build-up welding in vertical direction. Experiments with a z-increment of 2 mm, 1.5 mm, 1 mm and 0.75 mm were carried out.

Another challenge was to clad a ring (3). This was the precondition to weld the round geometries for the deep drawing tool. Particularly the optimal generation of the start and end point, which were at the same position, were in the focus of these investigations. Welding a ring caused a formation of a hole at the starting and ending point. This could be avoiding by using the two techniques: Firstly applying a longer welding track by using a rotation of up to 365° and secondly decreasing the laser power within a power ramp up to 300 ms. Both experiments led to a better macroscopic result. For further investigations the combination of a path of 365° and power ramp was used.

The setup for generating a flat ring (3) and the adjusted z-increment as with the vertical arranged tracks (2) were used for the next geometry, a multilayer build up welding of rings in vertical direction (4). First, superimposed rings were deposited. In this experiment the starting point of each ring was transferred by 45°. In a second variant a spiral path was used during vertical movement of the machine wherein the first and last ring were welded in one level.

The track offset of the seam tracks in horizontal direction had to be examined experimentally as well (5). For this purpose, rings were cladded with different overlapping offsets. It was tested to weld several rings from the outside to the inside and the other way round. The results of the experiments of vertical (4) and horizontal (5) overlapping rings were used to print the blank holder and the drawing die (7).

Manufacturing the geometry of the punch in one level was tested by using two different strategies (6). Firstly the inner filling was deposited by linear movements and the outer line by cladding a ring. This can be seen in Fig. 5a). Secondly the geometry was generated by welding a spiral in horizontal direction. Again the procedure from the outside to the inside and the other way round were tested.

Combination of the examined knowledge and cladding parameters were necessary to realize the additive manufacturing process by direct metal deposition of the three components (7).

The cross sections of all specimens were checked for detecting imperfections. Vickers hardness HV0.5 measurements were carried out on the cross section of the punch by using a Leco MHT Series 200 semiautomatic universal hardness tester. The distances between measurement points were 500 µm.

2.3 Deep drawing test

A punch force of 39 kN was estimated previously due to equation (Eq. 1). The circular blank was clamped between the blank holder and drawing ring with a defined clamping force. The blankholder force was applied by four helical compression springs and was set by adjusting the suspension travel. The required blankholder force was calculated by equation (Eq. 2). The calculated blank holder force was 2.3 kN. The acronyms and values for the equations and the parameters of the deep drawing test are given and explained in Tab. 2.

$$F_P = \pi * (d_1 + s) * s * R_m * 1{,}2 * \frac{\beta - 1}{\beta_{max} - 1} \quad (1)$$

$$F_{BH} = p_{BH} * A_{BH} \quad (2)$$

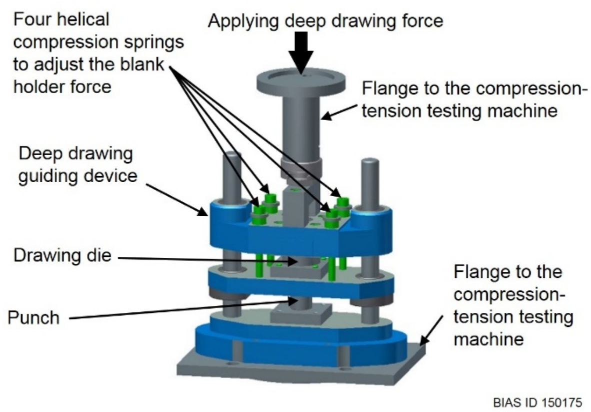

Fig. 3: Experimental set up for the deep drawing test

The kinetic for the deep drawing process was applied by 250 kN Zwick Roell Z250 compression tension testing machine. The punch travel and the forming speed were adjusted and the required punch force for the deep drawing test was measured. In a first test series for deep drawing investigations three samples were tested. The blank holder force was increased from 1.8 kN to 2.3 kN and to 2.9 kN. The force kept constant during the process. The lubricant was Wisura AK3080. The aim was to determine to optimal blank holder force to avoid wrinkle formation. While the blank sheet was pushed into the drawing die, the blank holder pressure increased progressively because of the decreasing area between the blank holder and the sheet. Using the determined blank holder force the second test series were carried out within cups were formed also in a lubricant-free deep drawing process.

Tab. 2: Parameters for the deep drawing test

Parameter	Symbols	Value	Unit	
Punch diameter	d_0	30	mm	Given cconditions
Hight of the cup	h	15	mm	
Sheet thickness	s	0.5	mm	
Punch- / drawring radius	r_P / r_{DR}	4	mm	
Tensile strength of the sheet	R_m	750	N/mm²	
Maximum drawing ration	β_{max}	2	/	
Blankholder pressure	p_{BH}	2.5	N/mm²	
Forming speed	v	10	mm/s	
Blank diameter	D_0	52	mm	Calculated
Drawring diameter	D_{DR}	31.4	mm	
Blankholder diameter	D_{BH}	31	mm	
Blank holder area	A_{BH}	905	mm²	
Drawing clearance	w	0.70	mm	
Drawing ration	β	1.73	/	
Punch force	F_P	39	kN	
Blankholder force	F_{BH}	2.3	kN	

3 Results and discussion

3.1 Additive manufacturing process

The investigated parameter set is documented in Tab. 3. It is to be noted that the use of a z -increment smaller than 0.75 mm lead to a risk of collision of the cladded track and the cladding nozzle. Therefor the increase of the build-up layer was larger than the traverse path of the machine.

Tab. 3: Process parameters investigated

Parameter	Symbol	Value	Unit
Laser power	P	2.5	kW
Velocity	v	500	mm/min
Powder feed rate	m_g	20	g/min
Z-increment	dy	0.75	mm
Overlapping	dy	2.0	mm

When using a z-increment of 0.75 mm the powder capture efficiency was around 67 %. Using a z-increment of 2 mm the capture efficiency decreased to 37 %. A z-increment of 0.75 mm amounted to 70 % track height.

With regards to the horizontal adjacent rings it is to be noted that welding from the outside to the inside is recommendable to observe a better geometry for the drawing die. The accumulated heat led to a higher inner layer ring which enabled milling of a sufficient radius geometry of 5 mm after laser deposition.

Using the spiral path was successful to generate the cylindrical shape. Applying ten levels led to a height of around eleven millimeters. The other technique of welding superimposed rings led to a lower capture efficiency. A height of around 8 mm was achieved when ten levels were deposited. The spiral path could not be used for generating the blank holder or drawing die geometry because of the horizontal arrangement. In this case the previous spiral was remelted when the next spiral was welded beside. To realize the geometries, horizontally arranged rings were cladded and the process repeated in vertical direction. Fig. 4 is showing the drawing die and the blank holder after the milling process. Some surface imperfections are visible at the drawing die but these did not have any negative influence on the deep drawing tests. The blank holder did not show any imperfections after the milling process.

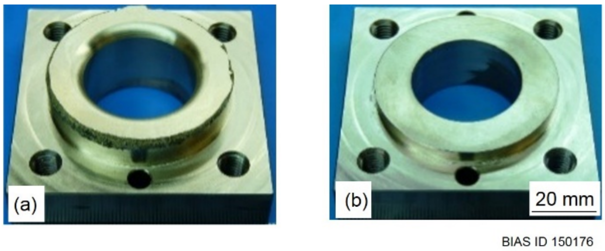

Fig. 4: Printed and milled drawing die (a) and blank holder (b)

The additive manufacturing process caused a high heat accumulation in the material. To protect the machine turntable against the heat, the process had to be interrupted occasionally. Every two layers the material was manually cooled down with compressed air for five minutes. For future additive manufacturing processes an additional cooling device should be applied. A high thermal distortion in the substrate was observed. Hence, the lower side of the substrate had to be milled parallel after the deposition process.

In Fig. 5 the generated punch is shown. Applying a spiral path in horizontal direction was not successful. It was not possible to create a flat area. As within the generation of the blank holder and drawing die, a high heat accumulation was observed during the additive manufacturing process for the punch. In addition waves were formed while welding the outer ring. The waves caused formation of some imperfections in the outer layer of the punch. This is visible in Fig. 5 (b) and (c). Another undesirable defect was observed. The inner area did not get high like the outer boundary. Hence, during the interruption of the process, the punch was manually filed parallel before continuing the process to avoid the continuation of these imperfections. The punch was cut in the center to analyze the metallurgy. Small pores could be detected. The diameters of the pores were up to 50 µm. No cracks were observed in the cross section. Hardness values were determined.

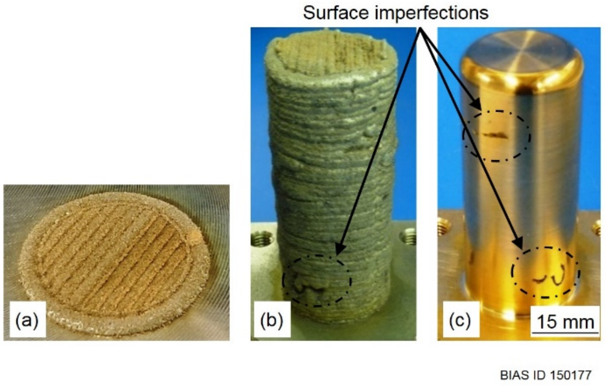

Fig. 5: First welded level of the punch (a), as-deposited (b) and milled (c) punch

Fig. 6 is showing the hardness distribution in the punch for three measurement lines. Two measurements on both sides and one in the center were done. The hardness values were at the same level as the substrate material and did not differ considerably from each other.

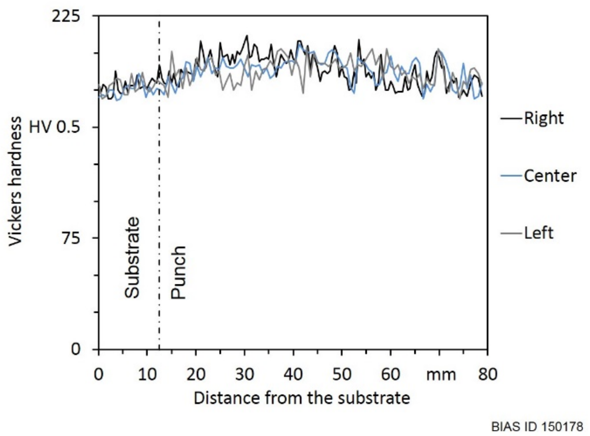

Fig. 6: Hardness distribution in the punch

3.2 Deep drawing test

In Fig. 7 the formed cups of the first deep drawing test are shown. The aim was to investigate the optimal blank holder force to avoid the formation of wrinkles. The blank holder force was increased within three steps from 1.8 kN to 2.9 kN. Within applying a blank holder force of 1.8 kN, wrinkle formation in the formed cup was observed. When the calculated blankholder force of 2.3 kN was used, the formation of wrinkles was avoided. But some small wrinkles were still visible. Increasing the blankholder force to 2.9 kN led to a smoother surface of the cup without any visible wrinkles.

Fig. 8 is showing the graphs of the deep drawing test. The higher punch force of around 26 kN was caused by the wrinkle formation scratching into the punch and drawing die. This effect did not occur when the higher blank holder forces were applied. It is to be noted that a higher blank holder force resulted in a higher punch force. With a punch stroke of around 22 mm the forming process was finished.

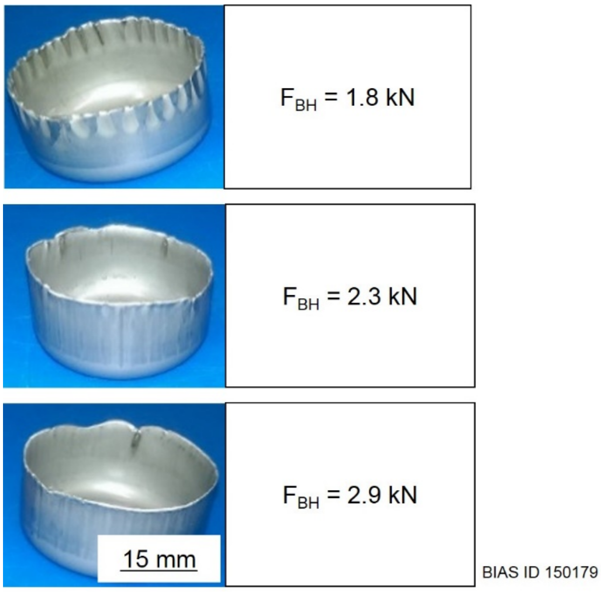

Fig. 7: Results of the deep drawing tests

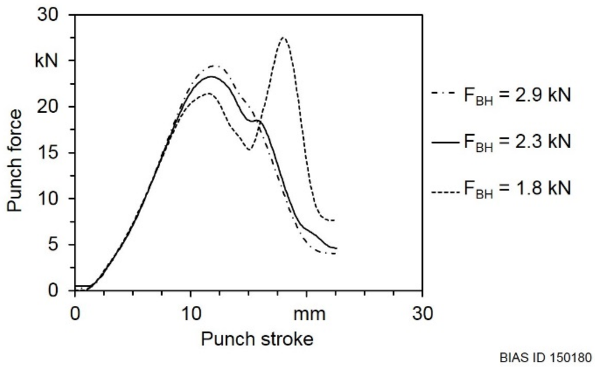

Fig. 8: Results of the deep drawing tests

In the next step the blank holder force of 2.9 kN was used for the next test series. The aim was to investigate the feasibility to avoid lubricant during the deep drawing process. Fig. 9 is showing the results. In each case three cups were formed with and without lubricant. The average of the maximum punch force was 26.4 kN ± 0.95 kN in the case of using lubricant. When the forming process was carried out without lubrication the average of the maximum punch force amounted to 27.73 ± 0.88 kN. Comparing the resulting punch forces it becomes clear that the average of the maximum punch force is just about 5 percent higher in the case of the lubricant-free process. The run of the measurements showed the same course. Within the punch stroke of around 20 mm the forming process was finished. All formed cups did not show any visible wrinkles and no cup base fractures were observed.

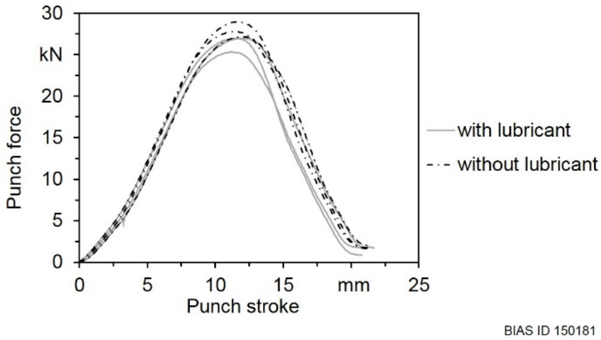

Fig. 9: Results of the deep drawing test with and without lubricant

4 Summary

A process was developed to generate a deep-drawing tool by direct laser deposition. The aim of the project was to take advantage of rapid manufacturing and produce near net shape tool parts by direct laser deposition of aluminum bronze as a powder and substrate material. A comprehensive parametric study was performed. The parametric study has contributed significantly to the understanding of direct laser deposition.

The hardness distribution of the generated drawing punch exhibited a constant hardness in the substrate and the punch. There were no cracks and imperfections were not greater than 50 µm.

The generated parts were successfully used to deep draw cups of 1.4301 steel with and without lubricant and wrinkles avoided by appropriate choice of blank holder force. Compared to the forming process with lubricant the average of the punch force was just about 5 percent higher.

Acknowledgment

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