LASER BEAM WELDING OF ATMOSPHERE ALUMINIUM DIE CAST MATERIAL USING HIGH FREQUENCY BEAM OSCILLATION AND BRILLIANT BEAM SOURCES

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Abstract

In serial production of components for automotive applications such as cooling and air-conditioning systems, aluminium die-cast material is frequently used due to its excellent castability. The aim of providing light weight components can be approached with thin walled cross sections even for complex structural parts.

However, cast components are usually connected to semi-finished products, such as profiles or tubes. The connections have to be mostly pressure tight. The joining technique for those applications has to be highly productive to obtain high component outcome as well as cost-efficient. Laser beam welding techniques are especially suitable for those tasks. Die-cast components have limited or no weldability due to their manufacturing process. Reasons for that are entrapped gases within pores or cavities under high pressure conditions. Furthermore, the mold release agents for the die-cast process are inappropriate for obtaining homogeneous and sound weld seams. Consequently, a high amount of pores in the weld seam and stochastic melt pool blow-outs occur, which prohibit mostly the use of the component. To solve these issues a new welding technique, remoweld®*T*, has been developed at Fraunhofer IWS. The unique method has been extensively tested and transferred to serial-production. The decisive step was to use laser sources with brilliant beam quality in combination with a high frequency beam oscillation within the melt pool. In this paper the technological approach will be presented. With the remoweld®*T* method it was possible to obtain homogeneous weld seams with low porosity and a strongly reduced distortion for the first time. Minor component tolerances and a reproducible joining technique with a high output for serial production can be achieved.

Introduction and Motivation

Modern light metal cast components contribute to a decisive extent on constructive lightweight, while at the same time contributing to the high functional integration of components. In particular, the production of delicate ribs to increase the component rigidity of structure relevant cast nodes and the formation of thin-walled pumps to complex crankcases with excellent mechanical and thermal durability, have become standard for automotive applications. This development is consistent with the achieved success by the current weight reduction of modern vehicles. The need for fossil fuels is reduced and thus the emissions from passenger cars. For light metal alloys, especially Al-based materials the atmospheric pressure die-casting method is mainly used to create complex part geometries. The limiting factor for further use of such components in structural lightweight designs is the lack of technical joining solutions. By using electron beam welding processes, some isolated applications for special purposes have been developed in the past.

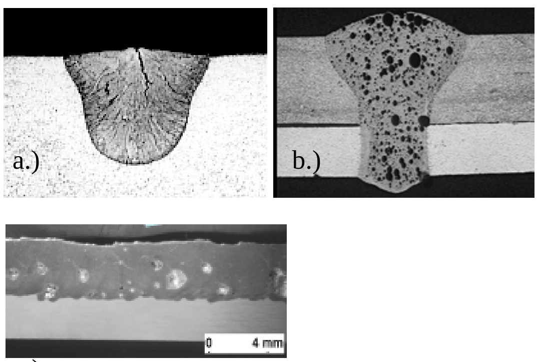
However, these unique solutions were bound to high costs due to insufficient development regarding serial production. The laser beam provides typically advantages for the production regarding cost savings and a high efficiency. One of the issues has been handling the molten phase, due to the high gas content in the die-cast material, leading to strong porosity and stochastically occurring melt ejections. Under such conditions, pressure tight weld seams could not be guaranteed [1,2,3]. In addition, the actual quality requirements demand a non-porous joint connection, which represents a challenge.

The current development of new laser beam sources introduces new promising alternatives. In recent years, the continuous development of laser sources and the considerable reduction in investment costs per kilowatt laser power has increased its attractiveness for mass production. Complemented by the availability of effective working optical systems for beam deflection, new solutions open up especially to overcome materials issues that prohibited laser welding solutions. The motivation was to develop new solutions for laser beam welding processes to meet and exceed the quality requirements. The developed approach at Fraunhofer

IWS was to actively influence the welding process by using high frequency beam oscillation and thereby increasing the weld quality significantly. The drastic reduction of pores in the weld metal and the avoidance of stochastic melt pool ejections was the focus of the investigation, to enable quality-oriented welds.

State of the art

Characteristic weld failures of die-cast aluminium can be caused by the formation of hot and solidification cracks and metallurgical and process-related pores, see Figure 1, [1,2,3]. A specific issue of aluminium die-cast alloys are interruptive melt pool ejections due to explosively released gas from the manufacturing condition. In the die-cast solidified matrix material, pores are present at stochastic intervals. Furthermore, die-cast material shows typically also very high hydrogen contents as stated in [4], thereby resulting in laser welding increased pores in the weld metal.



c.)

Fig. 1: Characteristic welding defects in aluminium or aluminium die-cast material: a) solidification cracking; b) pores caused by entrapped gases; c) process pores

The reasons for the typical pores and cracks in the weld metal of light metal alloys can be the following:

- hot cracks caused by solidification interval vs. chemical composition
- porosity caused gases by solidification interval (difference between liquidus and solidus temperature), see Figure 2
- process pores and blow outs caused by low viscosity of the melt metal.

While the first point cannot be influenced by laser beam welding process parameters for the 2nd and the 3rd issues high frequency beam oscillation can be helpful.

A very low solubility of hydrogen in the solidified aluminium matrix leads to the disposition of pores in the weld metal.

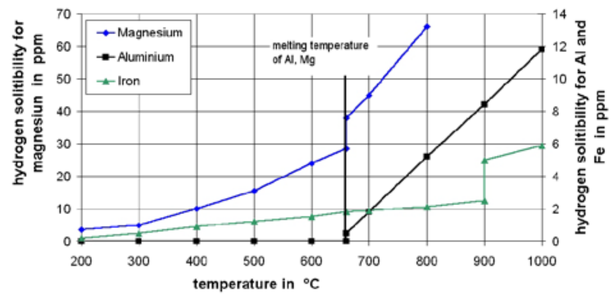


Fig. 2: Hydrogen solubility in the melt of the materials aluminium, magnesium and iron

With respect to the current welding solutions in the industry, mostly large spot diameters between 400 and 600 µm are used. These spot sizes lead to a large area that is covered by the laser beam and produces a large melt pool volume. That means, the amount of material heterogeneities which are covered by the laser beam is quite large. Furthermore, the danger of large and a high quantity of pores in the weld seam is very high and the melt pool cannot sustain the large amount of released gases due to the base material heterogeneities. The expected weld quality does not meet the quality assurance requirements, see Figure 3. From the foregoing considerations, it is clear that additional measures must be taken to achieve a good weld quality.

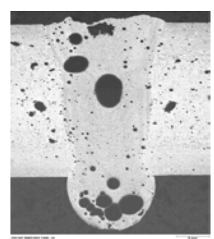


Fig. 3: Aluminium die-cast material (AlSi11) with 7,5 ppm hydrogen; welding parameters: P_L=3,0 kW, Spot 600 µm

The current answer to overcome these issues are static (e.g. twinspot, ect.) or dynamic guidance of the laser beam, see Figure 4.

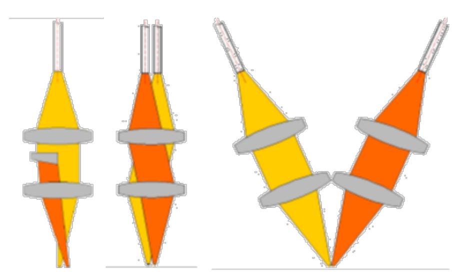


Fig. 4: Types of beam shaping with complex optics or additional beam sources [1]

The static beam shaping as a double or multiple focus has to ensure the extension of the melting pool to target the gassing of the melt. Due to the currently in the industrial environment often used large spot sizes of approximately 400 to 600 µm diameter in the focal point, a quite large melt pool will occur. That means more of the pressurized cavities in the die-cast material will be molten up and cause instabilities of the weld seam.

Moreover, since several years, laser beam welding is tested under vacuum to produce high quality welds. However, the complicated process technique and process control do not comply the well-known benefits of laser beam welding and economic advantages.

However, these approaches are not suitable to close massive melt pool eruptions and to ensure a homogeneous seam structure. Therefore dynamic beam shaping methods, such as the beam oscillation are under development [7,8]. By a rapid melt flow melt pool degassing should be supported [1,2,3,5]. Limiting in these approaches are the incapability to influence the melt pool dynamics by the laser beam, to remove gas bubbles and to guide the melt and to smooth the weld seam surface after a melt pool eruption. So far the available beam oscillation optics was primarily designed to move a static beam at various welding points within a defined field. The scanning frequency is usually limited to a maximum of one kilohertz.

Taking the mentioned approaches into account, they were not able to ensure keyhole stability during the entire welding process. The collapse of the keyhole and therefore a strongly fluctuating melt during the process cannot be prevented. Additionally, process-related pores are not completely avoided. The results of these events are spatter, massive ejections and a multitude of pores in the weld metal, see Figure 4.

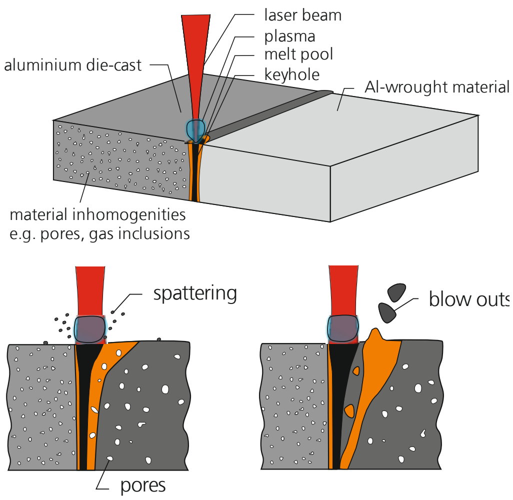


Fig. 4: Characteristic weld seam failures by using a static laser beam in aluminium die-cast material: spatter, pores, melt pool eruptions

Approach

Instead of using laser beams with a large spot diameter of approximately 400 to 600 µm and a laser power of up to 4 kW, for the new technological approach a single-mode fiber laser with a very small spot size (<100 µm) and low power (< 1 kW) will be used. To manipulate with high frequency the first commercially available scanner for macro processing is used. The particular property of that scanner is a very high scanning frequency of approximately 4 kHz in a working area of 1,5 x 1,5 mm². The scanner and it functionality was developed within a public founded research program, see [6]. Thus, a new beam tool for highly dynamic modulation of the laser beam available, see Figure 5.

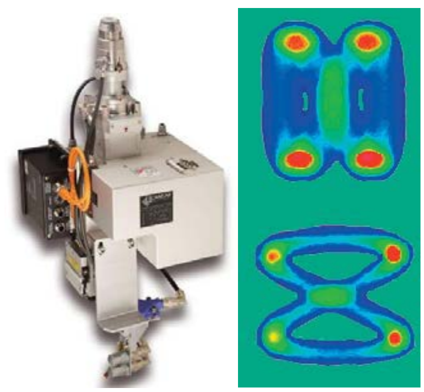


Fig. 5: left side: new high frequency scanner optics for macro processing; right side: Lissajous-scanning figure

In Figure 5 a typically Lissajous-scanning figure is shown. Furthermore is show the used optics, the so called Wel*DYNA* scanner unit, to provide high frequency beam oscillation [6, 9]. The advantage of the new welding approach is to influence the melt pool movement by using high frequency beam oscillation of those special scanning figures.

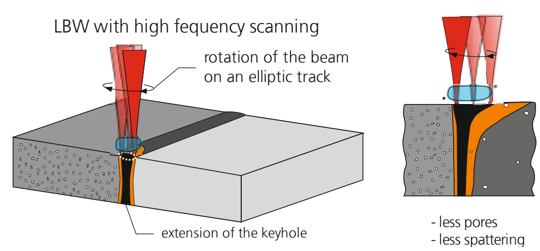


Fig. 6: Sketch of the high frequency beam oscillation within the melt pool area to influence the meld pool movement

Additionally, adapted to the specific conditions in the weld oscillation function, the laser power can be controlled along the beam shape. Through this high frequency 2D Lissajous-scanning figures can be mapped, which are superimposed on the welding feed movement. That approach allows potentially a fully different interaction between the molten bath and the laser beam. This provides the possibility of keyhole stabilization, in particular at acceptable welding speed. This new, highly dynamic beam oscillation extends the process parameter set with two components: a geometry component of the scanning figure and a resulting x, y amplitude variation. The technical challenge of the process is to define suitable beam oscillation parameters which provide an adapted melt pool dynamic to stabilise the keyhole. Furthermore, the current understanding of the interaction of the new technique can be described as follows. The basic theory is that due to the high frequency beam oscillation the beam "slices" and transfers the solid base material stepwise into the melt pool. The gas release of the base material cavities can be controlled by the geometric parameters of the scanning figure. Therefore the introduced gas in the melt pool is homogeneous and the process runs fully stable. Melt pool ejections can be softened and easier compensated from the process. Therefore, some high speed video sequences will be presented to support or negate the basic idea by experiments.

Experimental set-up and results

To describe the interaction between laser beam and material using high frequency beam oscillation, an experimental comparison to a static beam was carried out. Therefore the beam measurement (caustic) of a static beam and a circular shaped scan contour was conducted, see Figure 7, left hand side. On this example, the circle scan figure, a clear, uniform contour occurs even at high frequencies.

The current challenge is to determine appropriate optics configurations and process parameters for the experimental testing procedure. It has to be defined which scan contour is adequate to obtain the expected effect within the welding procedure. In the first step bead on plate tests with and without beam oscillation have been performed on rolled aluminium material. As a result, seen in Figure 7 (right hand side) clear process stabilization, associated with a drastic reduction of spatter for laser welding trials of magnesium-containing aluminium alloy is shown. The basic finding of this experiments shows that as the higher the frequency, the smoother the process. However, during the tests it became obvious that the welding results are depending on the amplitude of the beam deflection and the welding speed as well as from the welding depth. Imaging the keyhole appearance with a high-speed camera on the process time also confirm the higher stability against temporary melt pool movements which would lead without scanning to a partial or complete collapse of the keyhole. With the gained understanding of the process, the parameter interaction for die-cast materials can be reassessed.

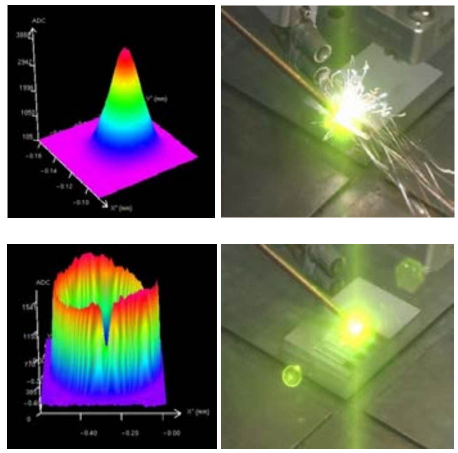
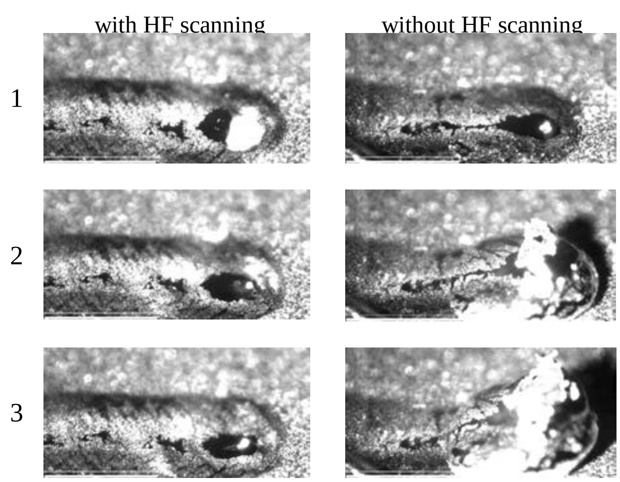


Fig 7: top left: caustic of a static laser beam, right photo of the associated process - many spatter; bottom left: caustic of a circularly shaped beam, photo of the associated process - homogeneous process with very little spatter

With this new technological approach a first study on die-cast material was performed. The above described trial with and without high frequency beam oscillation was performed on Al-die-cast material. Therefore high speed video sequence was recorded to see if the basic theory of "slicing" the material into appropriate process adapted melt volumes does work, see Table 1.



Tab. 1: comparison of melt pool appearance with HF scanning (homogeneous process) and static beam (melt pool ejection)

Within the experiments it was observed, that the liquid melt pool of a continuous high frequency scanned process was really smooth and mostly free of melt pool ejections. The standard process (static beam), on the other hand, showed continuously strong melt pool movements, spatter and finally explosively eruptions. In general there were drastically more heavily wavelike fluctuations of the melt pool surface. The melt pool was partially or entirely eliminated of the fusion zone. Reviewing the appearance of pores in several cross sections, it can be seen that the high frequency beam oscillation helps to reduce the amount of pores and there diameter. The stated approach that the beam "slices" and transfers the solid base material stepwise into the melt pool and the gas release of the base material cavities can be controlled are obvious. The small pores are carried to the surface by the melt pool current introduced by the high frequency beam oscillation. Therefore the gas, possibly also consisting of hydrogen, reacts probably with the melt pool and the hydrogen becomes interstitially frozen in the solidified material.

Industrial Application

An aluminium die-cast (AlSi9Cu) component was to be connected to a tube of wrought material (AlMg5), laser welding with high frequency beam oscillation was optimized and compared with conventional laser welding process. The challenge was to ensure a high stress, pressure-tight joint connection, which should be a media-tight in operation for years. Laser welding is the method of choice to produce integral, over the lifetime pressure-tight joint connections. With the previously conducted studies on rolled sheet and die cast material, the basis for the understanding of the interactions between high frequency oscillating laser beam and the material was gained. The findings were reassessed for the mixed compound from conventional die-cast and rolled semi-finished and create an application-oriented test matrix.

First examination was to determine the hydrogen content of the die-cast material. This was very high, namely13 ppm. First welding results with fixed beam confirmed the previously known findings. The result was a weld with a high amount of pores, Figure. 8.

The micrograph was taken from an area which was free of ejection. The weld at this point would be probably pressure tight. The danger for that weld seam is that under cyclic loading the webs between the pores fail and a slow lack of media would take place.

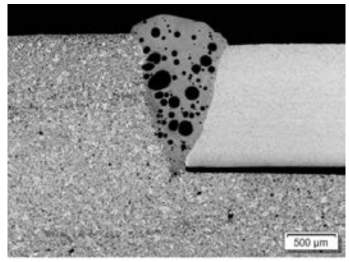


Fig. 8: Final result of a welded joint in die-cast and wrought using a static laser beam

The described welding approach of high frequency beam oscillation was experimentally adapted to the component and evaluated prototypically. To provide an industrial suitable welding process for the practice, extensive process studies were conducted. According to the preliminary tests, a suitable scan function was selected and determined experimentally the optimum process window regarding scan frequency and amplitude. The following tests were performed at constant laser power and welding speed to find out how tolerant the welding process reacts to changes in process parameters, see Figure 9.

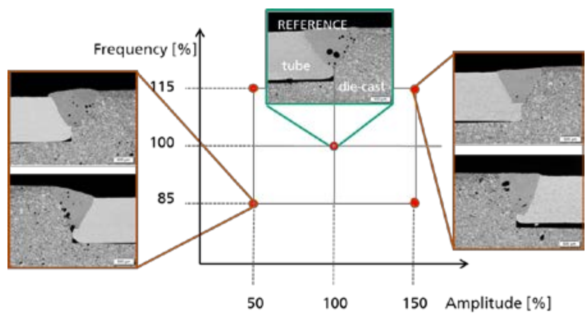


Fig. 9: Welding result of a weld seam between die-cast and wrought aluminium alloy using an oscillating laser beam; welding parameters (constant: laser power, welding speed, focal position of beam; beam oscillation parameters are variable)

The micrographs show weld seams with very few, sporadic pores, at nearly constant weld depth. The existing pores arrange themselves in the area close to the die-cast material. Furthermore, it can be observed, that the pores are not greater in size than those already present in the basic die-cast matrix. The risk of a webs breakthrough between the remaining pores and thus the failure of the weld is reduced drastically. The components that have been welded using this removeld®*T* technology were also successfully pressure tight tested after a shaker test at the customer.

The cross sections in Figure 10 were taken from samples which were performed at constant welding parameters, but they had a circumferential gap of either 0.1 or 0.2 mm. It is clearly shown that the gap size influences the welding depth. The larger the gap, the lower the welding seam is positioned in the joint. The number of visible pores grows with increasing amount of the molten die-cast material. Therefore, the intention of the laser welding process should be to melt as little die-cast material as possible. In addition the sample preparation should provide a zero-gap of the joint preparation.

Nevertheless, during the process moderate melt pool eruptions occur occasionally, but the effect to the weld seam is not as strong as it would be for conventional laser beam welding. The new welding technology allows besides closing these weld seam areas by remelting them again with the same process parameters.

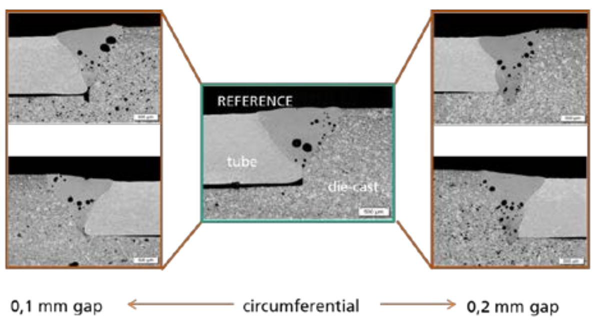


Fig. 10: Welding result of a weld seam between die-cast and wrought aluminium alloy; welding parameters (constant laser power, welding speed, focal position of beam; welding gap is variable)

The result of the new technology approach for laser welding die-cast material is a high process stability combined with a low failure rate of the component in the pressure test. In Figure 11, a typical cross section and a segment of the weld seam surface structure component are shown.

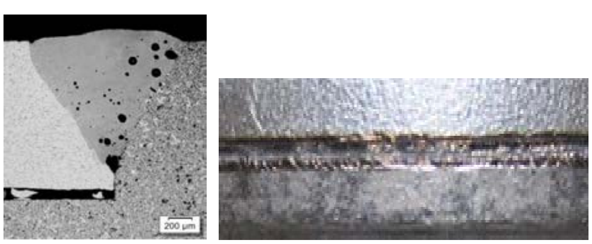


Fig. 11: left: cross section of a weld seam manufactured by high frequency beam oscillation between a die-cast material and a wrought component; right: top view of the same weld seam

Another component, extruded aluminium hollow profile section the technology of the high frequency beam oscillation was also tested. The component is shown in Figure 12. The aim was to join an extruded Al-alloy to a die-cast flange. This component is typically used in cooling of battery systems for electric mobility applications. The challenge in this case is, to ensure pressure tightness also for a segmented joint geometry. There are couple of weld seams which are connected perpendicular to each other and cannot welded in one path. Therefore it is needed to connect the weld seams pressure tight to each other. Nevertheless, the initial results of the first test welds show great potential for solving the issue. That underlines again the effectiveness of the selected technology approach – removeld®*T*.

Fig. 12: Laser welded cooling component consisting of hollow extrusion profile and a die-cast material

Summary

In this paper a new welding procedure to join aluminium die-cast material has been presented. The weld seams are pressure tight and welded with extremely low heat input. Distortion of the components is minimised and the weld seam appearance exhibits a high quality. With the remoweld®*T* welding technology the issue of welding aluminium die-cast material is solved for the described materials and wall thicknesses of the components. The welding process is very efficient and stable, thereby short cycle times are possible. In the near future also a laser welding head (remoweld®FLEX) available at Fraunhofer IWS Dresden which combines the 2D-scanner optics and process control unit (high speed camera and seam tracking sensors).

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