Porosity reduction in the laser beam welding of aluminium die cast alloys through the overlapping of mechanically induced sound waves

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Abstract. In recent years, to meet society’s increasing demands to reduce environmental pollution, the industry’s attention has been drawn to the subject of lightweight construction. Especially die-cast aluminium alloys offer their user a variety of design options for targeted weight reduction. However, a problem with the use of this material is the cohesive connection using welding technology. The main problem are the release agent residues as well as gas and oxide residues, trapped in the die-cast, which diffuse during the welding process in the direction of the liquid aluminium melt and result in a weld porosity. Due to the high heating and cooling rates resulting from the laser beam welding and the resulting outgassing possibilities of the liquid melt, the process of laser beam welding is particularly susceptible to the joining of aluminium die-cast components and, despite its many advantages, can currently only be used by complex and expensive additional measures. This is where the research activities of the Department for Cutting and Joining Manufacturing Processes (tff) start. The department deals with a specific influence on the prevailing melt flow through a sound wave superposition during the welding process. For the coupling of the sound waves, flexibly positionable piezoshakers are used, which allow greater degrees of freedom with respect to the welding geometry.

1. Introduction

In many areas of the mobility sector, the use of aluminium as a lightweight material is steadily increasing. The driving force behind this being the ongoing trend towards lightweight construction and the goal of reducing vehicle emissions and fuel consumption. The weight saving plays just as big a role as the possibility of combining the new materials as cost-effectively and with as little effort as possible. A large proportion of the aluminium components are die-cast products.

Die casting represents a process to produce near-net-shape, complex, and thin-walled lightweight components made of aluminium alloys, which is currently preferably used in various industries, such as the automotive industry or the energy sector. In current joining technical applications, such components are mainly connected by gluing or mechanical joining. However, an increased penetration and strong pore formations occur when laser beam welding these materials, so that central requirements for weld quality, such as pressure tightness, cannot be guaranteed. [12,14].

The laser beam welding of aluminium materials is often dominated using only special welding optics (e.g. double-focus optics) or the use of expensive welding consumables due to a low melt bath viscosity and the comparatively large molten bath volume of the molten aluminium. For example, comparatively high laser powers are required for welding with double-focus technology. Additionally, to the resulting economic disad-
vantages of the high energy input, component distortion and welding joint pass increase. Therefore, the development of a welding technique makes sense, with which in particular aluminium die-cast materials with lower laser power as well as dispensing with expensive welding consumables can be reliably joined. [3,9].

2. Solution Approach
By means of a deliberate superimposition of the laser beam welding process with mechanically induced sound waves, the approach of the Department for Cutting and Joining Manufacturing Processes influences the melt bath behaviour in a way that the user is provided with low-pore joining of die-cast aluminium alloys without the use of complex welding optics or expensive welding consumables. Here, the sound wave coupling takes place through the use of small and handy piezoshaker, shown in figure 1b, instead of hard-to-place sonotrodes whereby, higher degrees of freedom with respect to the welding geometry can be realized for the user (installation space and arrangement / sound direction).

Figure 1. Laser welding on an aluminium die casting alloy (t = 3mm) with high weld porosity (a), which can be significantly minimized by using small piezoshaker (b,c)

3. State of research and development

3.1 Laser beam welding of aluminium die cast alloys
In order to assess the weldability of a component, various sources [1,8] refer to the three impact factors weldability, weldability, and welding safety. As with all other metallic construction materials, weldability is also determined for aluminium by the extent to which the mechanical and technological properties are impaired by the welding process. For aluminium die-cast components, the hydrogen content is the decisive criterion for determining the weldability. Both pressing and fusion welding processes can be used for the joining of die-cast aluminium. The advantages in pressure welding processes are the prevailing high pressure and the avoidance of a molten phase, whereby pore formation is evaded. In the fusion welding processes, inert gas welding processes such as, for example, MIG and TIG welding processes are preferably used since, because of a low welding speed, the molten bath can better degas. Simultaneously, by using a pulsed welding current, the molten bath is set in vibration, thereby additionally causing active degassing.

In general, beam welding methods, which include electron beam and laser beam welding, are preferable to the conventional gas-shielded welding method in terms of lower component distortion due to concentrated heat input. In laser-beam welding of aluminium die casting the risk of pore formation is generally greater than in electron beam welding. This is often attributed to a better degassing in the vacuum. Whereas the laser welding process is very sensitive to disturbances. Consequently, when the molten zone of the laser beam fusion touches a gas trap or voids, the welding process is thrown out or interrupted and weakened in the load-bearing cross-section [4,8,17].

3.2 Influencing the melt flow in the welding process
Melt bath flows are not only a result of the feed movement during the welding process but also due to the so-called MARANGONI effect. The effect is due to the large differences in temperature between the capillary wall and the edge of the molten bath, causing different surface tensions to cause shearing forces. The chemical composition is the determining factor as to whether the surface tensions decrease or increase with increasing temperatures. This sets up two different flow directions in the molten bath, which lead either to wider or deeper melt baths. Below, different flow directions of the MARANGONI effect are illustrated, figure 2 [2,11].
A direct influence on the MARANGONI effect and consequently the resulting melt stream flows can be achieved through various external factors, as various publicly funded research projects have already shown. For example, in the course of the publicly funded project "MIXWELD" [16], it was shown that laser beam welding of mixed compounds made of austenitic and ferritic stainless steels in the thin sheet metal sector has a promising effect on the molten bath dynamics as a result of beam wobble. Another promising approach is disclosed in a paper by Watanabe et al. [20]. During welding, the filler metal is vibrated during TIG welding above the molten bath, thereby inducing sound waves into the melt. The propagation of sound waves in the melt causes local pressure and temperature changes due to emerging compression and decompression ranges. These permanently alternating pressure ranges cause cavities in the melt which cause flow turbulence as well as providing increased dendrite shear and nucleation during the solidification process [7].

This approach, adapted to steel materials, provides for the use of high-frequency beam oscillation ($f = 1500$ Hz), which significantly increases process stability and reduces seam imperfections, figure 3.

### Figure 2. Influencing the flow processes within the liquid melt by varying the surface tension [2,11]

### Figure 3. Possibilities of a beam oscillation crosswise to the welding direction (a), along the welding direction (b) as well as achievable weld seam qualities without beam oscillation (c) or with high-frequency beam oscillation (d) [10]

#### 3.3 Generation and visualization of sound wave

Mechanical vibrations in solid, liquid or gaseous media are referred to as sound and their spatial propagation as sound waves. In general, the characterization of the sound waves takes place via the frequency. Audible vibrations are referred to as auditory sound, whilst ultrasound, above a frequency of 20 kHz, is above the human hearing threshold [5,15]. One possibility for generating is the piezo-mechanical vibration excitation by so-called piezoshaker, figure 1b. In contrast to ultrasonic sonotrodes, which are very effective only in a certain frequency, piezo shakers work very efficiently over a wide frequency range. Furthermore, they can produce high forces and high vibration excitation. The mechanical oscillator has special stack actuators, which immediately set the piezo mechanics in motion by means of electrical pulses. The generated vibrations are transmitted via a plunger to the coupled body and this thereby being set into vibration [6,19].

The shearography camera known from non-destructive testing technology can be used to visualise the sound waves induced by piezoshaker or the resulting component vibrations, figure 4A.
This is an optical and therefore non-contact measuring method. The measured variable used in the shearography is the deformation gradient of the object surface. A shearography system consists of a coherent light source (e.g. laser diodes) and a shearography sensor. The coherent light is diffused at the surface of the optically rough test object and imaged and recorded by the imaging system and the shear element on the detector. Light or dark speckles are formed at each measuring point of the detector, by superposition of the reflected waves by constructive or destructive interference. The shear element thereby influences the sensitivity of the system by the shear amount and the shear angle. By calculating speckle images of the test object in two states (e.g., initial state and deformed state), the deformation of the object surface can be represented. In combination with a dynamic excitation (e.g., piezoshaker) shearography makes it possible to visualize forced component vibrations, figure 4C [13, 18].

4. Welding setup and parameters
To analyse the fundamental influence possibilities of sound wave superpositions on the melt bath dynamics, prevailing during the laser beam welding, simple component geometries in the form of aluminium die cast plates were used for the experiments. The selected material is an EN AC-43000 (AlSi10Mg) with a sample geometry of 100 mm x 80 mm and a die-cast material thickness of t = 3 mm. The specifications of the laser beam welding machine and the piezoshaker used for the sound wave superimposition of the welding process can be found in Table 1 below.

| Parameter set “1” | Parameter set “2” |
|-------------------|-------------------|
| Laser power       | 3,05 kW           | 3,2 kW           |
| Welding speed     | 3 m/min           | 3 m/min           |
| Focus diameter    | 600 µm            | 600 µm            |
| Shaker Frequency  | 23 kHz            | 29 kHz            |
| Shaker Amplitude  | 2 V               | 2,5 V             |

Table 2. Parameter sets used for welding.

| Laser Welding System                |
|-------------------------------------|
| Wavelength                          | 1,06 µm |
| Focus diameter                      | 400 - 600 µm |
| Laser power                         | max. 10 kW |

| Piezoshaker System                  |
|-------------------------------------|
| Frequency                           | max. 30 kHz |
| Amplitude                           | max. 3 V |
| Deflection piezo crystal            | max. 6 µm |
Before the actual test welds, the analysis of the vibration behaviour was carried out using the shearography camera. To be able to analyse the forming vibration patterns better, a differentiation based on the shear angle in the Y and X direction. Especially a shear angle selected in the X-direction enabled a very good analysis of the vibration patterns depending on the selected camera position, figure 5 b-d.

![Image](image_url)

**Figure 5.** Measurement setup within the laser welding cell (a) and visualization of the sound wave propagation at the component surface as a function of the shear angle (c, d)

First welding experiments with a sound wave superimposition were carried out, after analysing the vibration’s behaviour and the promising parameters derived therefrom. To be able to better estimate possible influences on the molten bath behaviour during laser beam welding, the relevant welding parameters (laser power, feed rate, focus diameter, and focus position) were kept constant. The parameters chosen for the experiments can be found in Table 2. The same applies to the distance of the shaker to the joining zone and the position of the clamping elements for fixing the test sheets in the welding device.

**5. Results**

With constant welding parameters, there is a clear difference between the pure laser beam welding process and the sound wave superimposed welding process. In a sound wave superimposed excitation in the ultrasonic range with a frequency of 23 kHz and an amplitude of 2 volts a significant minimization of the number of pores and pore size can be seen in cross sections. Similarly, interesting is the weld geometry itself. In a sound wave superposition, a significantly narrower weld material formation occurs in the root area, figure 7. To further verify the potential of the sonic waves induced by the piezoshaker for the associated influence of the melt pool dynamics, test samples with the aid of shearography measurements were used to identify areas of the joining zone in which there is no direct vibration excitation because of superposition of the standing waves. The excitation parameters and the resulting wave pattern were deliberately chosen to analyse the effect of such wave superposition on the welding result. The prepared cross sections show in these areas without stimulation a higher weld porosity, figure 7.

Since cross-sections reflect only a small area within the weld, a 3D weld characterization was performed using an X-ray microcomputer tomography (µ-CT) available at the University of Kassel, figure 6.

![Image](image_url)

**Figure 6.** Visualization of the pore distribution over the weld volume using µCT measurements in a sample without overlapping sound wave (above) and with overlapping soundwave (below)
Considering the μ-CT measurements based on sectional images along the weld seam, no significant difference in the pore size and number within the areas without and with sound wave superimposition can initially be determined. However, a comparison of the pore distribution over the entire weld volume based on a continuous cross section, figure 6 blue dots, shows a shift in the pore concentration within the weld metal. Because of a sound wave superposition, their concentration shifts toward the weld seam.

Based on the light-optical analysis of the weld joints in cross-section and a 3D weld seam characterization by means of μ-CT measurements, the potential of an in-process sound wave superposition of the laser beam welding process is already evident. To verify these positive results, hardness measurements were made across the weld cross section, figure 7.

The measured hardness values of the samples from the areas which have been excited have significantly lower hardness values in the transition between weld metal and base material than the comparative samples taken from areas without direct excitation. These so-called wave troughs show over the entire weld cross section consistent hardness values with a strong hardness drop in the transition to the base material. In order to confirm the result of the hardness measurements, the final step was the production of tensile specimens for the analysis of the mechanical-technological properties, figure 8.

Both the samples without sound excitation (0 kHz) and the tensile specimens with a corresponding sound wave superposition of 23 kHz failed in the weld area. The samples with a sound wave excitation of 29 kHz, however, failed in the base material. A look at the achievable tensile stresses indicates a fundamental improvement in weld strength because of sound wave superposition. As can be seen from the measured data, despite partial failure in the weld metal, the maximum achievable tensile stresses ($R_m = 220 \text{ N/mm}^2$) and the achievable strains in this context ($d_L = 5.7 \text{ mm}$) can be determined with a sound wave superposition of the laser beam welding process, which ultimately speaks in favour of a positive effect on the mechanical-technological properties.
6. Conclusion

With increasing demands on the weld quality, different approaches are being pursued to meet these high requirements. A promising method for improving weld quality is the integration of in-process sound wave excitation. In this method, which has been adapted from foundry technology, sound waves are used to produce different mechanical, metallurgical, fluidic and thermodynamic effects in the melt. Here, the use of the above-described handy and flexibly positionable piezoshaker to support the laser beam welding process is a cost-effective variant, with the complex 3D components (e.g., gearbox housing in automotive) made of die-cast aluminium alloys without the use of expensive welding consumables in combination with complex push-pull wire feed systems can be processed safely.

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