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The influence of ambient pressure during laser beam welding of aluminium high pressure die castings on the occurrence of weld bead porosity

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Abstract

Due to the occurrence of porosity and incomplete fusion, aluminium high pressure die castings are materials that are known to be difficult to weld. Porosity is mainly caused by hydrogen which is trapped within the weld bead during solidification as a result of insufficient degassing. This is aggravated by the increase in the solubility of hydrogen in aluminium by a factor of around 20 when the temperature of aluminium exceeds its melting point. Electron beam welding (EBW) and friction stir welding (FSW) are two state of the art technologies to minimise these defects. These methods use high frequency beam deflection to enhance degasification or welding below melting temperature to prevent the formation of porosity. Alternatively, common laser beam welding can be used as well but it has the drawback of high sensitivity to casting quality. However, laser welding under low or medium vacuum (VLBW) offers several well-known advantages, such as the increase of penetration depth or enhanced degasification when welding ferrous metals. Consequently, the current study focuses on the influence of reduced ambient pressure during laser beam welding on the occurrence of weld bead porosity when welding these materials. The investigations were carried out for various high pressure die casting materials from different levels of quality. All results are based on the outcome of x-ray computed tomography testing. It was shown that the overall weld bead porosity can be reduced and mechanical strength can be improved when welding under vacuum conditions.

Keywords: laser beam welding; vacuum; aluminium high pressure die casting

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1. Introduction

Despite many years of research, welding of aluminium die castings is still a challenge, due to the occurrence of porosity and incomplete fusion (Grov, 1998; Herrmann *et al.*, 2013; Niklas *et al.*, 2015; Nörenberg, 1991). Hereby, the porosity is mainly caused by hydrogen and incomplete fusion resulting from rapidly expanding inclusions or impurities within the die casting material. Depending on the gas content of the die casting, often measured by the density index (DI), the hydrogen content of aluminium die castings varies. Within the die casting part hydrogen is mainly present in form of hydrides, soluted gas and release agent remains. During the welding process the hydrides dissociate into hydrogen and metal as a result of the supplied process heat. The resulting hydrogen then forms gas bubbles inside the melt pool, moving towards the surface driven by buoyancy. In case the time the gas bubbles need to exit the melt pool is shorter than the time required for solidification, porosity results. To avoid the occurrence of weld bead porosity when welding aluminium high pressure die castings there are several welding processes which make use of different operating principles. Friction stir welding (FSW) for example, is performed at temperatures below the melting point and thus sharply reduces the temperature induced generation of porosity in general. Another example is tungsten inert gas (TIG) welding, which is performed at low welding speeds with a large melt pool. Both is beneficial for the degassing behaviour. In contrast to these advantages, TIG welding causes a high level of weld distortion and wide weld beads. Regarding FSW, the parts intended for welding have to absorb high clamping forces, necessary to ensure a sufficient joining the process. Therefore, beam welding is necessary in many applications. To produce narrow weld beads in die casting components, meeting high quality standards at a low level of weld distortion, electron beam welding (EBW) is named as method of choice (Pries *et al.*, 2002; Wiesner, 2003). In literature, laser beam welding (LBW) is described as a feasible process in general, but as the main challenge, a lack of fusion is reported (Pries *et al.*, 2002). Vacuum laser beam welding (VLBW) is another method of beam welding, which is predominantly investigated for welding ferrous metals. Several studies reported an overall calming effect on the melt pool, an increase of penetration depth and a reduction of weld spatter when performing laser beam welding at reduced pressure. (Katayama *et al.*, 2001; Luo *et al.*, 2014; Pang *et al.*, 2015) Therefore, the current study focuses on the influence of reduced ambient pressure during laser beam welding on the occurrence of weld bead porosity when welding aluminium die casting materials. (Wiesner *et al.*, 2001)

2. Materials and methods

2.1. Materials

The welding trials were carried out on two different aluminium die casting materials. Both materials were casted with vacuum assistance during the die casting process as test plates sized 260 x 150 x 4 mm. The plates were casted on a Bühler Evolution B53D die casting machine with a VDS ProVac 1000 vacuum system. The alloys casted were EN AC-AlSi10MgMn(Fe) (Material A) and EN AC-AlSi9Cu3(Fe) (Material B), where A is usually in a heat treated condition whereas B usually does not undergo a heat treatment. Aiming to assure a high casting quality, the density index (DI) was measured three times during the casting process and resulted in $DI_A = 0.8$ % for Material A and $DI_B = 0.8$ % for Material B. Material A was heat treated after welding to achieve the desired mechanical properties.

2.2. Laser beam welding

The laser beam welding trials were carried out using a solid state Yb:YAG disk laser (TRUMPF TruDisk6002D) with a wavelength of λ = 1030 nm and a beam parameter product of BPP = 8.0 mm × mrad. Moreover a TRUMPF BEO D70 processing optic with a focal length of 300 mm and an aspect ratio of 1.5:1.0 was used. Thus, the resulting focal spot size was 300 µm for the applied optical fiber diameter of 200 µm. The laser beam welds were performed as partially and fully penetrating welds (3 mm welding depth) aiming to investigate the weld bead porosity and the mechanical properties for both alloys casted. The partial penetration welds of 100 mm length were produced at different welding speed (v = 2/4/6 m/min) and ambient pressure (p = 1000/100/10/0.1 mbar). Full penetration welds were carried out on with a weld bead length of 250 mm and a welding speed of 2 m/min.

2.3. Material testing

As described above, partial and full penetration welds were performed during the underlying investigation. The weld beads were tested in two different ways: partial penetrating welds were examined by metallurgical and by x-ray computed tomography (CT) testing. Hereby, the penetration depth and the shape of the weld bead were measured, CT-scans were performed over the entire weld bead length. Full penetration welds were tested by x-ray computed tomography and tensile testing. Therefore, seven specimen according to DIN 6892-1 (Deutsches Institut für Normung, 2017) were taken from each weld bead by water jet cutting. Each parameter was welded three times on three different plates made from high pressure aluminium die casting.

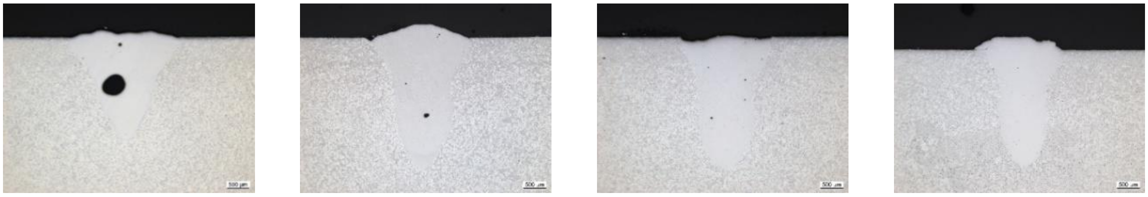
3. Results and discussion

Fehler! Verweisquelle konnte nicht gefunden werden. shows photographs of the welding process at varied ambient pressure, taken from outside the vacuum chamber. During the welding process, a strong decrease of weld spatter and the vapour plume was observed, as **Fehler! Verweisquelle konnte nicht gefunden werden.** indicates. The same observation was made for all materials and all welding speeds investigated.

a) p = 500 mbar b) p = 10 mbar c) p = 1 mbar d) p = 0.1 mbar

Fig. 1. Weld spatter and vapour plume at varied ambient pressure (welding speed 2 m/min) EN AC-AlSi10MgMn

Fig. 1 shows metallurgic cross sections from partially penetrating weld beads in EN AC-AlSi10MgMn(Fe). As Fig. 1 indicates, the cross sections were nearly free from porosity. In contrast, the result of the x-ray computed tomography analysis showed higher porosity contents than the metallurgic cross sections. Within the weld beads shown in Fig. 1 a) – d), a porosity content of 8/3/1.5/0,8 % was detected when welding at an ambient pressure of 1000/100/10/0.1 mbar. Moreover an average increase of the penetration depth of 30 % was measured when welding at an ambient pressure of 100 mbar or lower. Any further decrease of the ambient pressure has not caused a further increase of penetration depth.



a) p = 1000 mbar b) p = 100 mbar c) p = 10 mbar d) p = 0.1 mbar

Fig. 1. Metallurgic cross sections of typical welds performed with a welding speed of 2 m/min at varied ambient pressure.

The relation of ambient pressure, welding speed and porosity is presented in Fig. 2. The graph shows that the weld bead porosity decreases with sinking ambient pressure for all welding speeds tested. The porosity content of the weld beads is obviously influenced by the welding speed when welding under atmospheric conditions. Comparing the results for 1000 mbar and 0.1 mbar leads to the assumption that an influence of the welding speed on the weld bead porosity is lowered when welding under vacuum condition. These findings have not been statistically proven. However, the assumption that the weld bead porosity decreases with a reduction of ambient pressure during the welding process is supported by the fact that the same observation can be made for all welding speeds tested.

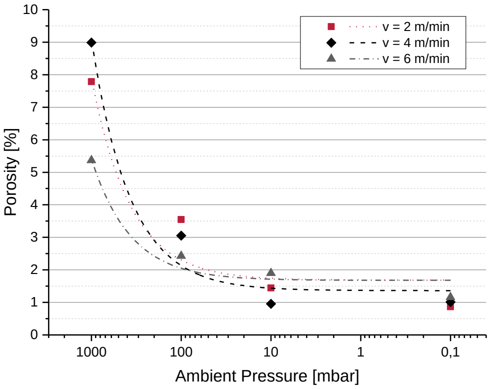
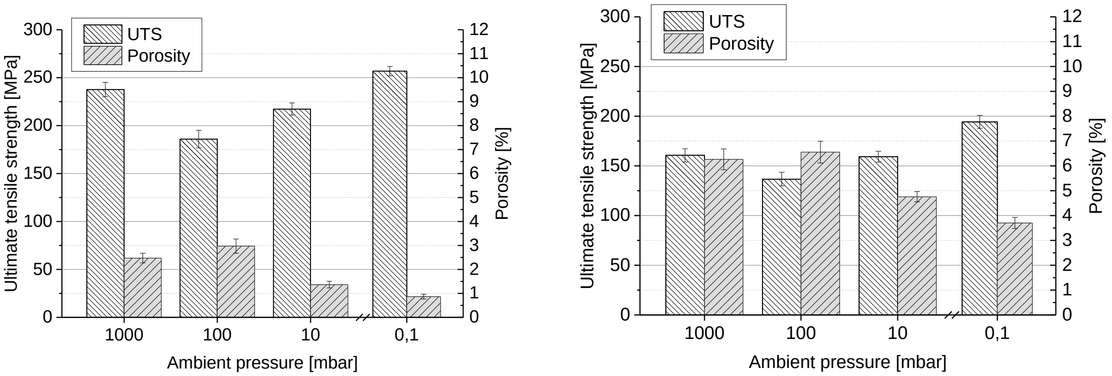


Fig. 2. Weld bead porosity as a function of ambient pressure and welding speed, for partially penetrating welds in EN AC-AlSi10MgMn(Fe).

From each full penetration weld bead seven specimen were taken, as described above. It was found that the position of the specimen within the weld bead had no influence on the weld bead porosity and the ultimate tensile strength. Consequently, the bar charts in Fig. 3 depend on 21 specimen per bar. The bar chart in Fig. 3 shows the results of the x-ray computed tomography analysis and the tensile tests of the full penetration welds. Hereby, the average porosity and the standard error are given for each ambient pressure stage. The welds were performed at a welding speed of 2 m/min and at varied ambient pressure. According to the charts in Fig. 3, the weld bead porosity decreases, when the welding process was performed at reduced ambient pressure and declined with the ambient pressure. The weld bead porosity reached a maximum at an ambient pressure of 100 mbar for both materials. The overall level of porosity detected within the weld beads made in EN AC-AlSi9Cu3(Fe) was higher than in EN AC-AlSi10MgMn(Fe). Moreover, Fig. 3 reveals that the ultimate tensile strength rises with declining weld bead porosity. In both cases the lowest porosity and highest ultimate tensile strength was observed when the weld bead was produced under an ambient pressure of 0.1 mbar. On the contrary the lowest values were found for welds produced at 100 mbar. In the case of EN AC-AlSi9Cu3(Fe) the weld bead porosity achieved at 100 mbar higher compared to the welds performed at 1000 mbar. As a drawback of welding aluminium die casting parts under reduced ambient pressure the decrease of the quality of the weld bead surface has been identified. The welds performed under vacuum condition, partially and fully penetrating welds, showed an increasingly irregular appearance on the weld bead surface. In addition it was found that the weld bead porosity within fully and partially penetrating weld beads showed a differing sensitivity when welding under atmospheric conditions.



a) EN AC-AlSi10MgMn(Fe)

b) EN AC-AlSi9Cu3(Fe)

Fig. 3. Bar chart of ultimate tensile strength (UTS) and porosity of the welds performed at varied ambient pressure for two different aluminium die casting alloys. The values are provided as means with standard error bars, based on 21 samples per bar.

4. Conclusions

The current investigation has shown several advantages and disadvantages when welding aluminium die castings at reduced ambient pressure. Welding under vacuum condition causes a significant reduction of the occurrence of weld spatter and the vapour plume. Moreover a 30 % increase of the penetration depth is observed when welding under an ambient pressure below ~100 mbar. Partial penetration welding as well as full penetration welding showed a decrease of weld bead porosity as a result of welding under reduced ambient pressure for curable (EN AC-AlSi10MgMn(Fe)) and non-curable aluminium die casting alloys (EN AC-AlSi9Cu3(Fe)). As a drawback of welding aluminium high pressure die castings under vacuum condition, a declining weld bead surface quality has been identified.

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