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Influence of filler wire and focus diameter on crack formation in laser beam welding of high strength aluminum alloys

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Abstract

Light weight components for automotive industry become more important with increasing demand for electronic driven vehicles. Up to now, high strength aluminum alloys have a wide use in aerospace sector. To establish these alloys also in automotive sector, the development of improved welding techniques are required. However, due to its alloying elements magnesium, zinc, silicon and copper which increase solidification interval, the weldability of high strength aluminum alloys of 5xxx, 6xxx and 7xxx series is limited by hot crack formation. Hence, metallurgical as well as systemic approaches are needed to enable weldability of these alloys. The present paper discusses the influence of different filler wire materials and spot diameters on hot cracking. Therefore a disc laser is used to weld aluminum alloys without and with filler wire. Mechanical and metallographic analysis display quality of welds. In particular, tensile tests, microhardness measurements and cross sections are shown in order to compare welds of 5xxx, 6xxx and 7xxx. It results that a small focus diameter of 340 µm by trend reduce hot crack formation for AA 6082-T6 and AA 7075-T6 due to low heat input. Moreover, the use of filler material decreases also hot cracking, while AlSi5 can be identified to have highest influence with respect to avoid hot crack formation for the hardenable alloys.

Keywords: Joining, laser beam welding, high strength aluminum alloys, hot crack formation

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1. Introduction

High strength aluminum alloys continuously become more important in automotive industry by increasing need of light weight components especially for electronic driven vehicles. Up to now, however, fusion welding of these alloys, especially of 7xxx series, is rarely used due to low weldability. Hence, the use of 7xxx alloys is only established in aerospace sector Ostermann, 2007. Therefore, the development of improved welding techniques is needed. To reach this aim, different challenges have to be managed. Especially the alloying element zinc in 7xxx series and Mg in 5xxx series is causing spatter formation due to the low evaporating temperature with high vapor pressure in the keyhole. Moreover, the hot crack phenomena caused by content of copper in combination with magnesium and silicon with a high solidification interval significantly decreases weldability Schulze, 2010.

To overcome these problems, several strategies are possible to be pursued. In detail, adjustment of alloy composition in weld seam can be performed by using filler material. Due to the high content of globular grains and decreased mean grain size in the weld, the permeability in semi solid state is expected to increase. This enables higher value of feed rate of liquid in the mushy zone and hence decreases the hot crack susceptibility Katgerman et al., 2008. Furthermore, measures by processing technology e.g. variation of focal diameter or total energy input can be implemented for influencing solidification conditions in weld seam towards reduced crack formation.

2. State of the art and need of further investigations

2.1. Filler material

In order to reduce crack formation in arc welding of AA 6060, Coniglio, 2008 used AlSi5 as filler wire with the effect of grain refinement in the weld. With a content of 16 % filler dilution instead of no filler, the mean grain size was reduced from 63 µm to 51 µm. In general, a higher content of Si leads to reduced solidification shrinkage and an increased interdendritic liquid quantity, which decrease the hot crack susceptibility in the weld. Huang et al., 2015 investigated the influence of Sc content on grain refinement in a 7xxx series alloy welded by metal inert gas with AlMg6Sc filler. Due to an increase of Sc content from 0.1 wt.% to 0.25 wt.% in the base material, the grain size decreased from 120 µm to 50 µm. Due to fine coherent Al3 (Sc, Zr) particles heterogeneous nucleation was induced. Furthermore, Wloka, 2007 reached grain refinement at laser beam welded AA 7050 with Sc-doped AlMg6Sc filler. Owing to the fact that costs are high and availability is low, alloys or filler material with Sc are hardly appropriate for industrial implementation.

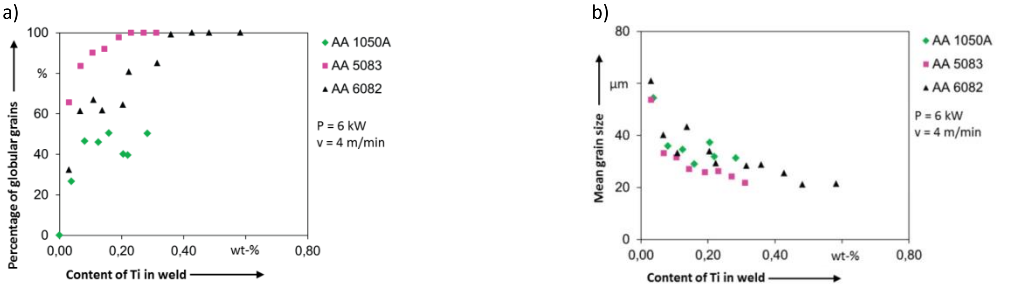

Fig. 1: Influence of Ti content in laser welds on a) percentage of globular grains and b) mean grain size for different aluminum alloys AA 1050A, AA 5083 and AA 6082 Tang 2014

Besides the use of Sc as nucleation element, Ti show also potential to enable grain refinement. In the work of Tang, 2014 the influence of filler wire with different contents of Ti and B on grain refinement, mechanical properties and hot crack susceptibility in laser beam welded AA 5083 and 6082 is shown (Fig. 1.). Experiments regarding casting of aluminum by Wang et al.. 2013 state that besides Ti also Zr, Nb and V act as grain refining elements due to a growth restriction effect at concentrations of 0.1 wt.% to 0.5 wt.%. It was also measured a decrease of grain size of about 50 % by using 0.25 wt.% Zr compared to 0 wt.% Zr at casting.

2.2. System technology

Regarding the overview of Cross et al., 2008 on hot crack theories, hot cracking depends on a critical strain rate which is generated by the local thermal strain conditions and solidification shrinkage as well as liquid feeding. If the critical strain rate is reached, the pressure drop in liquid films between dendrites initiates crack formation presuming impurities. This suggests that besides alloying strategies, measures regarding system technology enable a decrease of hot crack formation during welding.

Hu et al., 2006 implemented an additional heat source in order to reduce strain rate during cooling. Experiments with hybrid laser-gas metal arc welding of AA 7075 show decreased transversal crack occurrence of the weld by applying a heat source besides the weld. Also a reduced welding speed with least possible heat input was found to reduce hot cracks.

Also in pulsed heat conduction laser beam welding of AA 6016 Bergmann et al., 2013 could reduce hot cracking in bead on plate welds by using superimposed diode laser beam on welding area. In order of increased solidification time, the reduced hot crack susceptibility is believed to occur.

2.3. Need of further investigation

Studies mentioned above regarding fillers wire used specifically casted filler material, which are commercially not supplied. Regarding ISO 18273:2004, there are few filler materials available on basis of AlSi and AlMg which contain silicon and titan, i.e. AlSi5 and AlMg4.5Mn. Up to now, it is not known, if the advances of high contents of alloying elements with grain refining effect can be assigned to standardized filler material with lower content of these alloying elements. Furthermore, the grain refining effect of silicon containing filler wires during laser beam welding of AA 7075 is not known. Therefore, the influence of AlSi5 and AlMg4.5Mn filler wires on hot cracking needs to be investigated.

Regarding processing technology, the positive effect of elongated solidification time and changed strain conditions was shown. However, additional heat sources were needed for implementation.

The present paper, therefore, aims to clarify the effect of silicon containing filler wire and different laser beam intensities in order to reduce hot crack susceptibility in laser beam welding. I.e. the influence of beam diameter and filler material for high strength aluminum alloys AA 5083, AA 6082 and AA 7075 on hot crack formation is discussed. Since AA 5083 has lowest hot crack susceptibility and shows no softening effect, this alloy is used as reference in order to compare results regarding irregularities in weld besides hot cracking. The analysis of hot crack length is measured by cross sections, surface grindings and longitudinal sections. Metallographic inspections and tensile tests as well as microhardness tests were performed in order to discuss the influence of hot cracks and the softening effect on mechanical properties.

3. Experimental setup

3.1. Welding setup

All experiments were performed with a disc laser with a wavelength of 1,030 nm and a maximally continuous power output of 4 kW. Two different optics were used for welding, a 2D galvanometer scanner with a focus diameter of 340 µm and an optic with resulting focus diameter of 600 µm, which was handled by 6-axis robot in order to carry a wire feeder. The wire feed was installed in trailing position, which ensured a continuous feeding of the filler wire with 0.8 mm diameter.

The used clamping device ensures a reproducible position of all specimens and provides clamping perpendicular to sheet surface plains. All welds were performed with shielding gas Ar 4.6 with mass flow of 20 l/min from top side and 5 l/min from root side of the weld. The used samples with dimensions of 150 mm x 50 mm x 1 mm were milled and cleaned with isopropanol at joining edge before welding. The rolling direction was parallel to welding direction. In consideration of a full penetration weld, parameters of laser power and welding velocity were set to values, which enables smooth surface of weld seam and root. When using filler material, the velocity of filler wire was set equal to welding velocity in order to obtain no sag of the seam. A list of chemical composition of used base materials and filler wires is given in Table 1.

Table 1: Used aluminum alloys and filler material with their contents of alloying elements according to EN 755-2 and ISO 18273:2004

Aluminum alloys content [wt.%]	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
AA 5083(AlMg4.5Mn)	0.4	0.1	0.1	0.4-1.0	4.0-4.9	0.05-0.25	0.25	0.15	rem.
AA 6082 (AlMgSi1)	0.3-0.6	0.5	01	0.4-1.0	0.6-1.2	0.25	0.1	0.1	rem.
AA 7075 (AlZn5.5MgCu)	0.4	0.4	0.5	1.2-2.0	2.1-2.9	0.18-0.28	5.1-6.1	0.2	rem.
Aluminum filler content [wt.%]	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
Al 4043 (AlSi5)	4.5-6.0	0.8	0.3	0.05	0.05	-	0.1	0.2	rem.
Al 5183 (AlMg4.5Mn)	0.4	0.4	0.1	0.5-1.0	4.3-5.2	0.05-0.25	0.25	0.15	rem.

3.2. Metallographic and mechanic characterization

Metallographic analyses of cross sections, surface grindings and longitudinal cross sections were carried out by light microscopy. Therefore, all samples were grinded and polished to 1 µm and etched. In order to determine the amount of hot cracks in weld seams, all cross sections, surface grindings and longitudinal cross sections are examined for hot cracks by light microscope and length of single cracks were summed up to accumulated length.

For the analysis of the tensile strength, the samples were laser beam cut and milled at parallel length in order to remove thermally influenced zones. The specimen geometry is according to standard DIN 50125 shape “H”. Tensile tests were performed on a tensile tester with continuous test velocity of 5 mm/min.

Hardness measurements were carried out according to Vickers with a microhardness tester using 1 N of test load during 20 s measurement time for each measuring point. The Measurements were performed as lines, positioned in the middle of cross sections with a resolution of 0.4 mm (0.2 mm in region of narrow weld seams) between single measurement points. In total a distance of -8 mm and +8 mm relative to weld seam center was adjusted in order to determine hardness of weld seam, heat affected zone and base material.

4. Results and discussion

4.1. AA 5083 welding

For reference regarding welding quality, AA 5083 samples were welded without filler by spot sizes of 340 µm and 600 µm and with spot diameter of 600 µm using filler materials Al 4043 (AlSi5) and Al 5183 (AlMg4.5Mn) according to Table 1,. Metallographic inspections in Fig. 2 show representative specimens with small irregularities in cross sections. Small shrinkage grooves and rough weld seam surface occur in cross section of weld seams performed with 340 µm spot size, see Fig. 2a) and with 600 µm spot size, see Fig. 2b), which may cause super elevation of tension. Cross sections performed with AlSi5 filler and with AlMg4.5Mn filler show weld reinforcement, see Fig. 2 c) and d). Pore formation can be detected in all weld seams with uncritical dimensions in terms of mechanical strength.

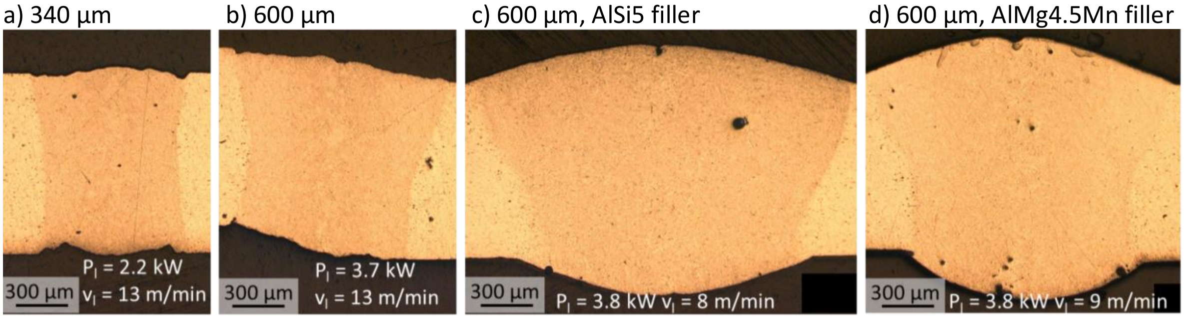

Fig. 2: Cross sections of welded AA 5083 a) 340 µm spot diameter, b) 600 µm spot diameter, c) 600 µm spot diameter and AlSi5 filler and d) 600 µm spot diameter and AlMg4.5Mn filler

In order to map weld seams in three dimensions, surface grindings and longitudinal cross sections were carried out. Within these analyses, no crack formation or other weld defects as mentioned in cross sections are detected. As AA 5083 and both filler materials are not hardenable aluminum alloys, the weld seam is not expected to be softened during welding. This can be examined by microhardness tests, shown in Fig. 3.

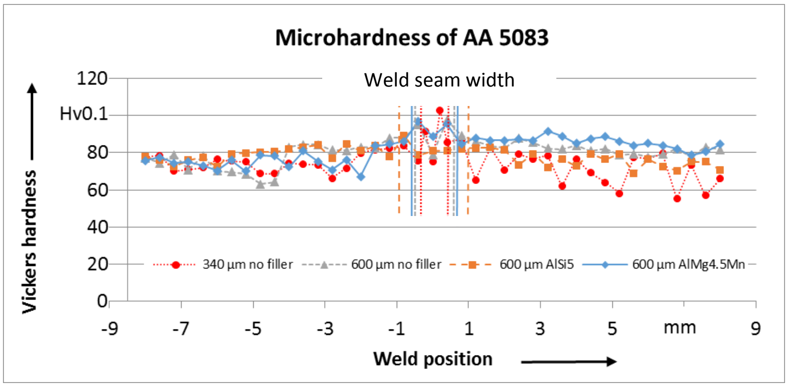

Fig. 3: Microhardness measurement HV0.1 of weld seams generated with different beam diameters and filler materials at a total length of 16 mm over cross sections with indication of weld seam position (dotted lines)

Except a small increase of hardness at regions of weld seams without filler material and with AlMg4.5Mn filler to about 90 HV0.1, the hardness is about 70…80 HV0.1. This nearly homogenous contribution of microhardness across weld seams results in similar tensile strengths for all four configurations at a level above minimal strength of base material, as it can be seen Fig. 4. Considering the standard deviation of all results, no significant influence of focus diameter or filler material can be achieved.

Even weld defects, i.e. the occurrence of small shrinkage grooves at weld seams made without filler material and small linear offset at welds with 600 µm spot diameter (compare Fig. 2 a) and b)) do not influence the tensile strength. However, the fracture location of all tensile test specimens welded without filler wire is in weld seam. Tensile test specimens welded with filler material fracture in base material. This behavior leads to the conclusion that no cracking occurs in every sample of AA 5083 material and small weld defects have no influence on tensile strength.

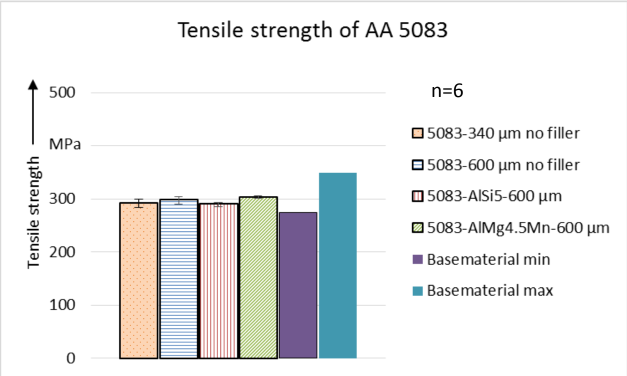

Fig. 4: Tensile strength of laser beam welded AA 5083 samples without filler material, with AlSi5 filler and with AlMg4.5Mn filler in comparison with maximal and minimal value of base material according to (EN 755-2)

4.2. AA 6082-T6 welding

AA 6082-T6 specimens were welded without filler wire by using 340 µm and 600 mm spot diameter and with two filler materials referenced in Table 1. The resulting cross sections of AA 6082-T6 welds can be seen in Fig. 5.

a) 340 µm b) 600 µm c) 600 µm, AlSi5 filler d) 600 µm, AlMg4.5Mn filler

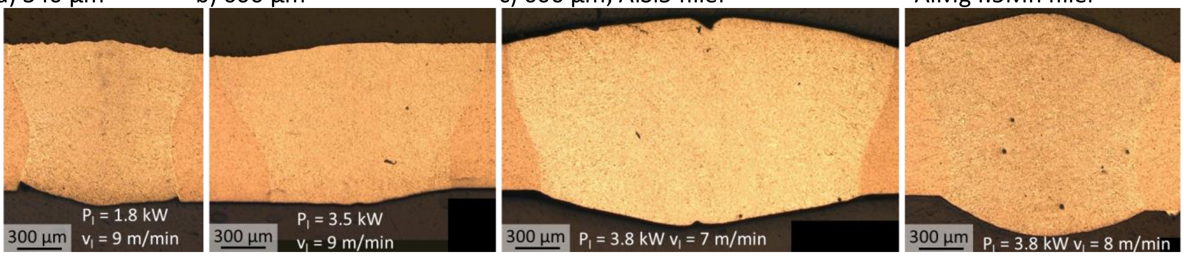

Fig. 5: Cross sections of welded AA 6082 a) 340 µm spot diameter, b) 600 µm spot diameter, c) 600 µm spot diameter and AlSi5 filler and d) 600 µm spot diameter and AlMg4.5Mn filler

Due to low content of volatile elements e.g. Mg or Zn in base material, volume loss during welding is expected to be small. Hence, an even surface of the weld seam can be achieved with weld reinforcement. Pore formation in dimensions below 50 µm can be detected also, which are considered to have no influence on mechanical properties.

Evaluation of accumulated hot crack length in grindings reveal that welding with small focal diameter of 340 µm results in reduced hot crack susceptibility compared with 600 mm spot diameter, as it can be seen in Table 2. The use of small focus diameter effects lower heat input and therefore reduced strain during solidification. By using filler material, no hot cracking was found. Due to the addition of silicon and magnesium by use of AlSi5 and AlMg4.5Mn filler, the hot crack susceptibility decreases in the weld. At this investigation, it cannot be clarified, if this is owed to grain refinement.

Table 2: Accumulated length of hot cracks at surface grindings and longitudinal cross sections for AA 6082 specimens (magnification: 20X; measurement length: 20 mm)

Accumulated length of hot cracks in AA 6082	Surface grinding top side [mm]	Surface grinding root side [mm]	Parallel cross section [mm]	Total length [mm]
340 µm, no filler	0.7	-	0.1	0.7
600 µm, no filler	3.2	-	0.7	3.9
600 µm, AlSi5 filler	-	-	-	-
600 µm, AlMg4.5Mn filler	-	-	-	-

Due to the hardenability of AA 6082 alloy, a softening at weld seam and heat affected zone can be detected by microhardness measurements, which are shown in Fig. 6. Microhardness at the weld seam center is about 60 HV0.1 for all configurations.

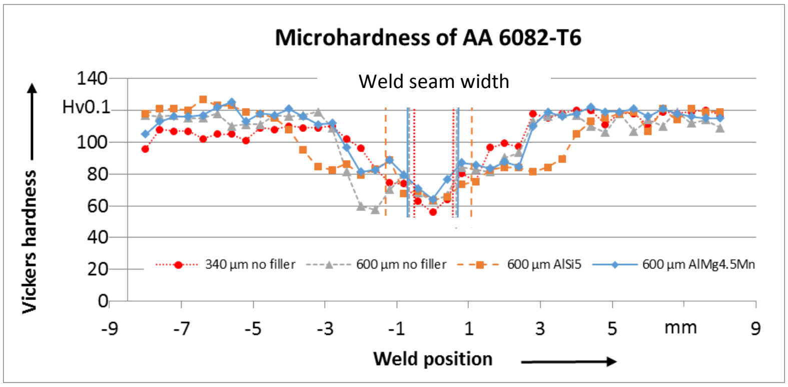

Fig. 6: Microhardness measurement HV0.1 of weld seams generated with different beam diameters and filler materials at a total length of 16 mm over cross sections with indication of weld seam position (dotted lines)

Due to lower energy input during welding with 340 µm spot diameter, the heat affected zone is smallest with also smallest influence on softening. Weld seams without filler and with AlMg4.5Mn filler show similar width of heat affected zone. In correlation to high weld seam width, shown in Fig. 5c), the heat affected zone stretches about 3 mm to each side of weld seam. Owing to a very similar maximum of softening in weld seam center, tensile strength is expected to be influenced mostly by hot cracks.

Tensile tests of the discussed weld seams show that welding without filler material and a focus diameter of 600 µm results in the lowest tensile strength with 230.1 ± 5.4 MPa. Using 340 µm spot size enables increased tensile strength of 241.1 ± 3.2 MPa. The fracture location is in seam center for all welds without filler material which can be explained by rough surface and hot cracks in weld seams. The higher strength of weld seams, welded with 340 µm spot size, correlates with smaller accumulated length of hot cracks given in Table 2. This fact consolidates that a small focus diameter enables a decrease of hot cracking at AA 6082 due to lower heat input, which results in low strain during solidification.

The use of filler material enables higher tensile strengths with nearly the same values for both filler materials. In detail, use of AlSi5 filler results in strength of 264.4 ± 1.2 MPa and use of AlMg4.5Mn results in 270.7 ± 1.8 MPa. However, the strength of the base material of 310 MPa cannot be reached even though without hot crack formation. This can be explained due to softening effect and verified with location of fracture, which is in all tensile test specimens in heat affected zone for both filler wires in correlation to width of decreased mircohardness (see Fig. 6). Due to reduced stress in the increased area at reinforced weld seam, the location of fracture is not in weld seam.

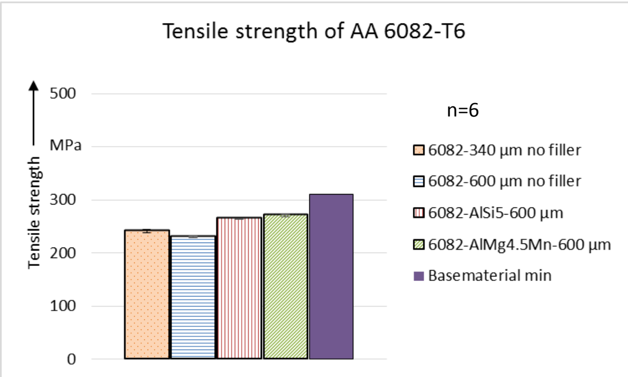

Fig. 7: Tensile strength of laser beam welded AA 6082 samples without filler material, with AlSi5 filler and with AlMg4.5Mn filler in comparison with minimal value of base material according to (EN 755-2)

4.3. AA 7075-T6 welding

Specimens of AA 7075-T6 welded without and with filler materials referenced in Table 1 show no hot cracks in cross section polishes (see Fig. 8). Due to containing Mg and Zn in basematerial, high evaporation pressure occurs, which affects in rough surface topology and reduction of cross sections when welding without filler material

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a) 340 µm b) 600 µm c) 600 µm, AlSi5 filler d) 600 µm, AlMg4.5Mn filler

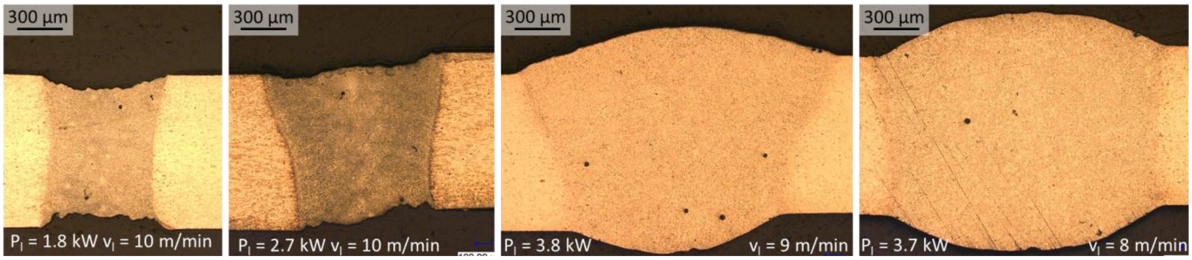

Fig. 8: Cross sections of welded AA 7075 a) 340 µm spot diameter, b) 600 µm spot diameter, c) 600 µm spot diameter and AlSi5 filler and d) 600 µm spot diameter and AlMg4.5Mn filler

The use of filler wire enables a compensation of volume loss generated by evaporation and spatter formation. Hence, a smooth surface with weld reinforcement compared to welds without filler wire results. Evaluation of accumulated length of hot crack in grindings, see Table 3, reveal that in tendency, welding with a small focal diameter of 340 µm results in lowest hot crack susceptibility, whereas 600 µm spot diameter shows a slightly increased accumulated length of hot cracks. The use of filler wire enables significant reduction of hot crack number but no total avoidance. However, it can clearly be ascertained that AlSi5 filler strongly reduces hot cracking compared to AlMg4.5Mn. Both filler materials decrease hot crack susceptibility due to changed concentrations of alloying elements. If filler materials result in grain refinement is not clarified in this work. Besides AlSi5 and AlMg4.5Mn filler material, filler with zircon, e.g. AlMg4.5MnZr containing 0.1…0.2 wt.% zircon, is expected to further decrease hot cracking due to grain refinement. According to Wang et al., 2013 this amount of zircon results in grain refinement of 50 % compared to no content of zircon.

Table 3: Accumulated length of hot cracks at surface grindings and longitudinal cross sections for AA 7075 specimens (magnification: 20X; measurement length: 20 mm)

Accumulated length of hot cracks in AA 7075	Surface grinding top side [mm]	Surface grinding root side [mm]	Parallel cross section [mm]	Total length [mm]
340 µm, no filler	7.7	3.1	2.4	13.1
600 µm, no filler	5.8	5.8	5.1	16.7
600 µm, AlSi5 filler	-	-	0.2	0.2
600 µm, AlMg4.5Mn filler	0.2	1.0	0.3	1.5

In order to analyze softening of weld zone, Fig. 9 shows mircohardness measurement of all four combinations. It can be seen that softening occurs by using 340 µm spot diameter with slightly harder state of 123 HV0.1 compared to all other welds with 105 HV0.1. The heat affected zone of welds with filler materials shows similar hardness distribution and let expect therefore similar strength if similar content of hot cracks occurs.

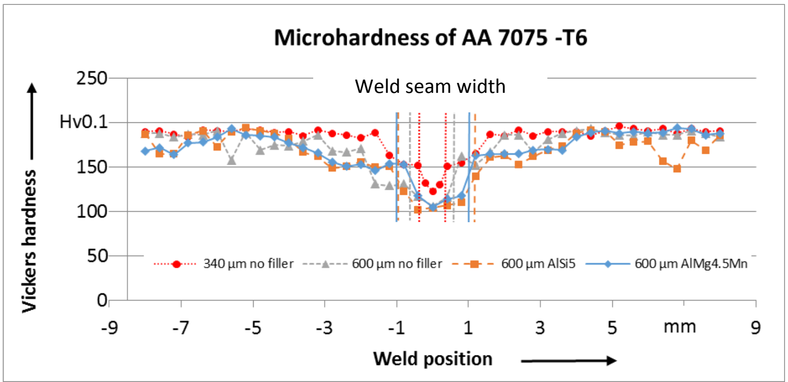

Fig. 9: Microhardness measurement HV0.1 of weld seams generated with different beam diameters and filler materials at a total length of 16 mm over cross sections with indication of weld seam position (dotted lines)

Tensile strength of specimens welded without filler wire shows smallest values of around 300 MPa due to hot cracking and volume loss in cross sections. High standard deviation in range of 20…30 MPa allow no statement of influence of spot diameter on hot crack formation. Calculation of tensile strength with the lower cross section of welds using 340 µm spot diameter compared to 600 µm (see Fig. 8 a) and b)) would result in increased values. This is in addition a hint of beneficial effect on hot cracking when using small focus diameter.

The use of AlSi5 filler material significantly increases tensile strength to 390 ± 9.1 MPa compared to no use of filler and AlMg4.5Mn filler material, which results in 325± 26.1 MPa. This is in good correlation with low hot crack length (see Table 3). However, the strength of the base material cannot be reached due to hot cracking in the weld seam and softening in the fusion zone. As in results regarding AA 6082, it can be assumed, that due to grain refinement effect of silicon, which was investigated by Coniglio, 2008, hot cracking decreases. However, hot cracking cannot be significantly reduced with reduced heat input when using small focus diameter. Hence, further decrease of total heat input during welding without filler wire would lead to decreased hot cracking.

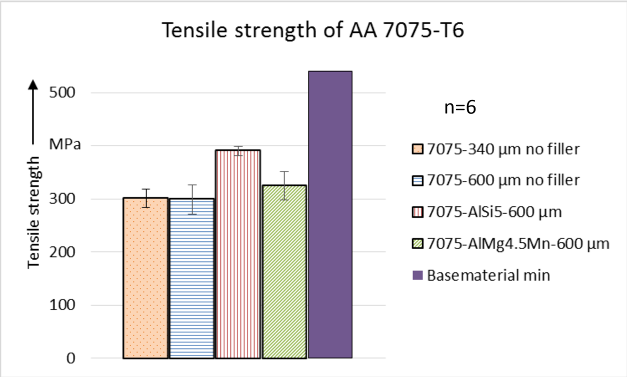

Fig. 10: Tensile strength of laser beam welded AA 7075 samples without filler material, with AlSi5 filler and with AlMg4.5Mn filler in comparison with minimal value of base material according to (EN 755-2)

5. Conclusion

For conclusion regarding the influence of focus diameter and filler material on hot crack formation in laser beam welding of AA 6082-T6 and AA 5083 it can be concluded that a small focus diameter of 340 µm reduces hot crack formation due to decreased heat input in comparison to 600 µm spot diameter. This was shown by accumulated crack length in weld seam and tensile tests. Hence, low heat input by using small focus diameter can be recommended to decrease hot cracking. Furthermore, in weld seams in AA 6082-T6 sheets performed with AlSi5 filler material no hot cracking could be detected by metallographic inspections. However, softening decreases tensile strength to 87 % compared to base material in T6 state. AlMg4.5Mn filler material also reduces hot cracking compared to welds without filler, but not completely.

Reduced heat input slightly decreases hot cracking during welding of AA 7075-T6 without filler wire. The influence of filler wire in welding of AA 7075-T6, however, is significant in regard of tensile strength, wherein AlSi5 wire enables about 20 % higher values compared to AlMg4.5Mn filler. Due to quite similar shape of weld seams, same development of microhardness across fusion zone and low hot crack length, AlSi5 filler wire can be identified to significantly reduce hot cracking. This can be explained by grain refinement with reduced solidification shrinkage and an increased interdendritic liquid quantity with high content of silicon as it was mentioned in Coniglio, 2008. However, the present work did not consider grain refinement by measurements, wherefore this evidence misses.

In future work, age-hardening or tempering has to be investigated in order to increase microhardness in softened region of fusion zone with the aim to evaluate maximal reachable level of tensile strength compared to base material. Furthermore other filler materials e.g. AlSi12, AlMg4.5MnZr or AlCu6MnZrTi with grain refining elements Ti and Zr have to be evaluated to further decrease or even avoid hot cracking by grain refinement as shown in Wang et al., 2013 and to increase mircrohardness due to content of copper. Moreover, the influence of welding speed and energy per unit length as well as further decreased focus diameter has to be investigated in regard of hot crack formation.

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