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Application of an analytical model to predict the grain structure of laser beam welds in aluminum alloys

Christian Hagenlocher[a*], Artur Leis[a,b], Florian Fetzer[a], Daniel Weller[a], Rudolf Weber[a], Thomas Graf[a]

[a]*Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*
[b]*Graduate School of Excellence advanced Manufacturing Engineering, Universität Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany*

Abstract

The grain structure of a weld influences its hot crack susceptibility during welding and its strength after completion of the welding process. Simple analytical equations to predict the grain structure of laser beam welds in AlMgSi aluminum alloys are proposed. The model describes the influence of the welding parameters on the morphology as well as on the size of the grain structure. Metallographic analysis of laser beam welds show, that the analytical model predicts the grain structure in sufficient accuracy. These findings explain how to optimize laser beam welding processes in order to obtain a reliable formation of an equiaxed dendritic grain structure or to reduce the grain size. Further, these findings outline the parameter field for the formation of an equiaxed dendritic grain structure in additive manufacturing processes.

Keywords: Laser beam welding; grain structure; solidification; aluminum alloys; selective laser melting; additive manufacturing

1. Introduction

The grain structure of a laser beam weld in aluminum alloys has a strong influence on the strength of the joints, as shown by Wyrzykowski and Grabski, 1986 and on the susceptibility of the weld to the formation of hot cracks, as shown by Braccini et al., 2000 and Hagenlocher et al., 2019. Welding with different welding parameters leads to different grain structures. Fig. 1 shows horizontal sections of full penetration laser beam welds in AA6016. The samples were grinded and polished from the surface, etched according to Barker at

* Corresponding author. Tel.: +49 (0)711 685 66855; Fax: +49 (0)711 685 66842.
E-mail address: christian.hagenlocher@ifsw.uni-stuttgart.de

30 V for 60 s, and illuminated by polarized light. The samples were welded with different welding parameters. Although the width of the welds is almost the same, the grain structures are significantly different. Fig. 1a shows a weld, which contains exceptionally oriented dendritic grains. In the grain structure of the weld shown in Fig. 1b equiaxed dendritic grains occur irregularly. This indicates an unsteady solidification behavior during the welding process. Fig. 1c shows a weld with a constant presence of a zone of equiaxed dendritic grains in the region of the weld seam center.

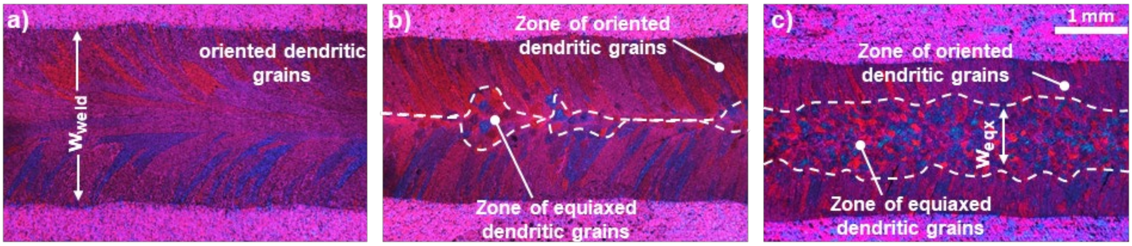

Fig. 1. Horizontal sections of full penetration laser beam welds in s = 2.4 mm thick AA6016 sheets welded with a beam diameter of 50 µm, a velocity of 1 m/min, and a laser power of 835 W (a), a beam diameter of 100 µm, a velocity of 3 m/min, and a laser power of 1500 W (b), and a beam diameter of 600 µm, a velocity of 6 m/min, and a laser power of 4300 W (c).

In order to deliberately influence the grain structure of laser beam welds, the knowledge about the impact of the three major welding parameters laser power, welding velocity and laser beam diameter is mandatory. In the following, a simple analytical model is presented that predicts the grain structure of laser beam welds as a function of these welding parameters.

The same model might be applied for additive manufacturing to predict the grain structure in each individual weld seam during selective laser melting (SLM) of aluminum parts. The majority of these parts show exceptionally an oriented dendritic grain structure as published by Thijs et al., 2013. However, an equiaxed dendritic grain structure would be beneficial to obtain isotropic mechanical characteristics of the generated parts.

The grain structure model presented by Hagenlocher et al., 2019 allows to predict the grain structure of a weld. The model provides explicit analytical expressions which were derived from the two dimensional heat conduction equation of Rosenthal, 1946. To ease the understanding of the results the model is summarized in the following.

2. Model

In order to describe the temperature field of deep penetration laser beam welding the Bessel function in the Rosenthal equation for two-dimensional heat conduction can be simplified with

$$K(\xi) \approx \sqrt{\frac{\pi}{2\xi}} \cdot e^{-\xi} = e^{-\frac{v \cdot \sqrt{x^2+y^2}}{2 \cdot \kappa}} \cdot \sqrt{\frac{\pi \cdot \kappa}{v \cdot \sqrt{x^2+y^2}}}, \qquad (1)$$

where v is the welding velocity and κ the thermal diffusivity, as shown by Heller et al., 2017. With this simplification, the temperature gradient at the centerline of the weld (*y = 0*) and at the liquidus isotherm $T = T_{Liquidus}$ is

$$G(P_{Depth}, v) = \frac{2 \cdot \pi \cdot (T_{Liquidus} - T_{amb})^3 \cdot {\lambda_{th}}^2 \cdot v}{{\eta_{abs}}^2 \cdot {P_{Depth}}^2 \cdot \kappa}, \quad (2)$$

as shown in Hagenlocher et al., 2019. Where $T_{amb} = 20°C$ is the ambient temperature, λ_{th} is the heat conductivity, η_{abs} is the absorptance, which can be calculated according to Gouffé, 1945. The depth specific power

$$P_{Depth} = \frac{P_{Laser}}{s_{Weld}}, \quad (3)$$

is the ratio of the incident laser power P_{Laser} and the welding depth s_{Weld}.

As stated by Kurz and Fisher, 1986 and Kou, 2003 the ratio $G/_R$ between the local temperature gradient G and the local solidification rate R determines the morphology of the grain structure. At the centerline of the weld the solidification rate *R(y=0)* equals to the welding velocity v.

Equation (2) divided by the solidification rate *R(y=0)* (i.e. the welding velocity v) and solved for P_{Depth} yields the minimum required depth specific power

$$P_{Depth,eqx} = \sqrt{\frac{2 \cdot \pi \cdot (T_{Liquidus} - T_{amb})^3 \cdot \lambda_{th} \cdot \rho \cdot c_p}{{\eta_{abs}}^2 \cdot G/_{R_{eqx}}}} \quad (4)$$

to obtain a local ratio $G/_R$ beneath the critical ratio $G/_{R_{eqx}}$ for the formation of an equiaxed dendritic grain structure in the weld center area.

3. Results

Kurz and Fisher, 1986 presented a solidification structure map for aluminum alloys with a solidification temperature range of $\Delta T_{sol} \approx 50$ K. This applies for example to high strength aluminum alloy AA6016 used in car body production and to the casting alloy AlSi10Mg used for selective laser melting processes. From this the criterion $G/_{R_{eqx}} < 3^{+0.5}_{-0.5} \frac{Ks}{mm^2}$ for the formation of an equiaxed dendritic grain structure can be derived.

Equation (4) was solved for laser beam welding of AA6016 and for selective laser melting of AlSi10Mg as powder. The material characteristics of AA6016 and of AlSi10Mg are listed in Table 1.

Table 1. Material characteristics of AA6016 and AlSi10Mg, as given in Cammer, 1995 and Vončina et al., 2006.

Parameter	Abbreviation	Laser beam welding of AA6016 sheets	Selective laser melting of AlSi10Mg
Liquidus temperature	$T_{Liquidus}$	652°C	585°C
Heat conductivity	λ_{th}	211 W/mK	150 W/mK
Density	ρ	2700 kg/m³	2700 kg/m³
Heat capacity	c_p	896 J/kgK	910 J/kgK
absorptance	η_{abs}	0.8	0.11

The absorptance for laser beam welding was chosen according to Gouffé, 1945 as described in Hagenlocher et al., 2019. The absorptance in selective laser melting equals to the absorptivity of aluminum *A = 0.11* under the assumption of a capillary with a very low aspect ratio << 1.

Fig. 2 compares the calculated depth specific power threshold resulting from equation (4) with experimental results, which are represented by the normalized width $w_{eqx,norm} = \frac{w_{eqx}}{w_{weld}}$ of the zone of equiaxed dendritic grains. This normalized width results from the ratio of the width of the equiaxed zone w_{eqx} to the width of the weld w_{weld}. Both quantities were measured in horizontal sections as described in Fig. 1.

In case of laser beam welding of AA6016 the solution of equation (4) yields the minimum depth specific power $P_{D,eqx,6016} = 677^{+65}_{-50}\,\frac{W}{mm}$, which is required for the formation of an equiaxed dendritic grain structure. This threshold-value is represented in Fig. 2 by the vertical blue line. The vertical green line represents the minimum depth specific power $P_{D,eqx,AlSi10Mg}$ for the formation of an equiaxed dendritic grain structure in selective laser melting of AlSi10Mg calculated with equation (4) and the values listed in Table 1. The width of the colored zones corresponds to the uncertainty of ${}^{G}/_{R_{eqx}} < 3^{+0.5}_{-0.5}\,\frac{Ks}{mm^2}$.

The results of the laser beam welding experiments are represented by the blue data points and published in former work (Hagenlocher et al., 2019 and Hagenlocher et al., 2019 and Hagenlocher et al., 2018). The results represent the average value of minimum five analyzed experiments and the length of the error bars represent the range between the minimum and maximum measured values.

The green symbol represents the normalized width of the zone of equiaxed dendritic grains in an individual seam of an aluminum part generated by selective laser melting (SLM). This part was produced with typical parameters of selective laser melting, i.e. a velocity of 78 m/min, a laser power of 420 W, and a beam diameter of 100 µm focused on the surface of the sample.

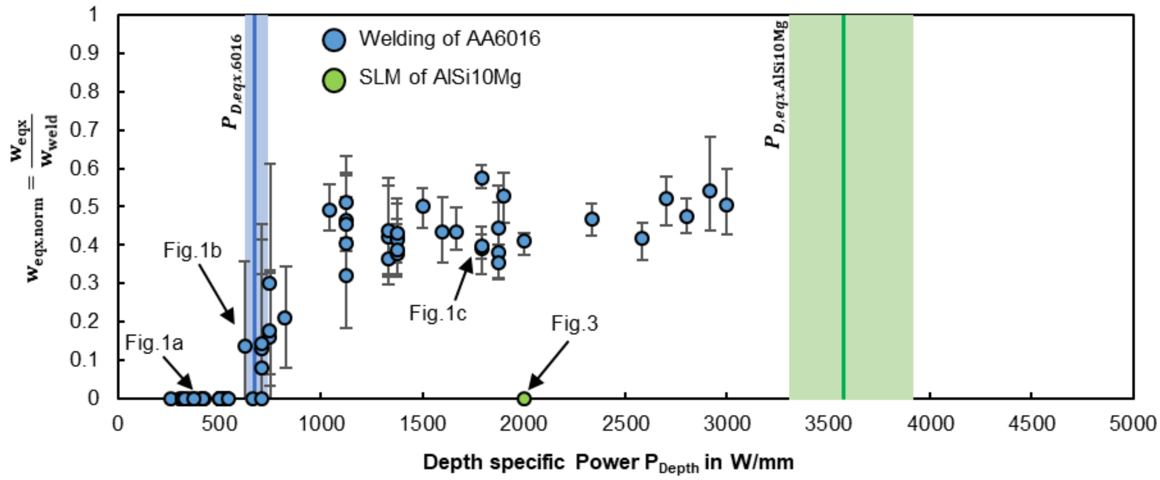

Fig. 2. Normalized width of the zone containing equiaxed dendritic grains as a function of the depth specific power P_{Depth}.

The experimental results agree very well with the result of equation (4) in case of laser beam welding of AA6016. Welds welded below $P_{D,eqx,6016}$ do solely show oriented dendritic grains and welds welded above $P_{D,eqx,6016}$ show an equiaxed dendritic grain structure. Furthermore, the threshold calculated with equation (4) explains the unsteady solidification seen in Fig. 1b: The corresponding parameters used for this weld lead to a depth specific power P_{Depth}, which is close to the critical depth specific power $P_{D,eqx,6016}$.

In the case of selective laser melting of AlSi10Mg equation (4) yields the minimum depth specific Power $P_{D,eqx,AlSi10Mg} = 3573.7^{+341}_{-265} \frac{W}{mm}$ for the formation of an equiaxed dendritic grain structure. The large difference between this threshold value and the actual depth specific power $P_{Depth} = 2000 \frac{W}{mm}$ of typical process parameters actually used for selective laser melting of AlSi10Mg explains, why solely oriented dendritic grains form in these parts.

Fig. 3 verifies this prediction with a sectional view of an individual seam of the corresponding additively generated part. The seams of the layer were generated with a feed rate of 78 m/min, a laser power of 420 W, and a beam diameter of 100 µm focused on the surface of the sample, as represented with the green symbol in Fig. 2. The section was grinded and polished, etched according to Barker and illuminated with polarized light. As predicted above no equiaxed dendritic grains can be found in the grain structure of the additively manufactured part.

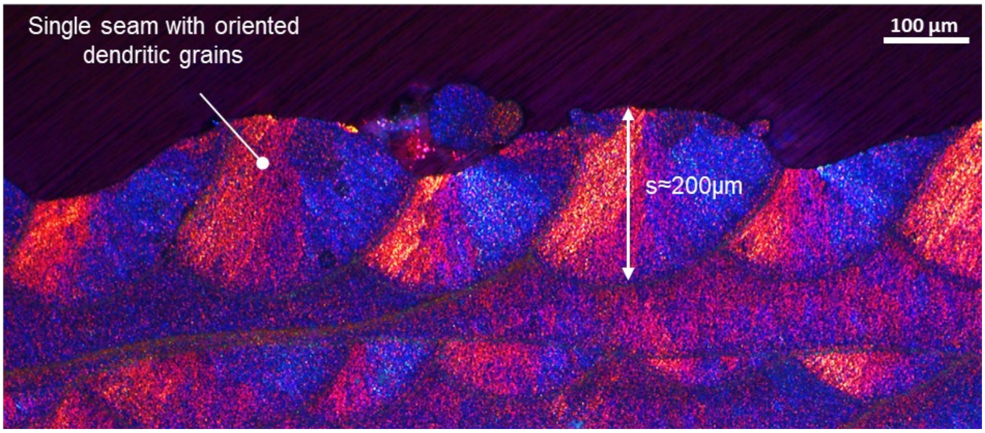

Fig. 3. Sectional view of a AlSi10Mg part generated by selective laser melting with a beam diameter of 100 µm, a velocity of 78 m/min, and a laser power of 420 W.

The high value of the minimum depth specific power of $P_{D,eqx,AlSi10Mg} = 3573.7^{+341}_{-265} \frac{W}{mm}$ explains, why the majority of the additively manufactured parts do not show an equiaxed dendritic grain structure.

In order to obtain an equiaxed dendritic grain structure in additively manufactured parts, the depth specific power P_{Depth} has to be increased. This requires either an increase of the spot diameter, an increase of the feed rate or spatial beam oscillation processes, as described by Hagenlocher et al., 2019.

4. Conclusion

The novel explicit analytical equations of the grain structure model allow to predict the morphology of the grain structure of laser beam welds. The power per depth was identified to be the key parameter for deliberately influencing the grain structure. The results of the presented grain structure model agree very well with the experimental measurements in case of laser beam welding of AA6016. It further explains the unsteady solidification behavior found in welds, which were welded close to this threshold.

Additionally, the model was applied for selective laser melting of AlSi10Mg. It was found, that the current parameters typically used in this process are far below the calculated minimum depth specific power, which is required for the formation of an equiaxed dendritic grain structure. This explains, why an equiaxed dendritic grain structure is usually not found in parts generated by means of selective laser melting.

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References

Braccini, M., Martin, C. L., Suéry, M., Bréchet, Y., 2000. Relation between the mushy zone rheology and hot tearing phenomena in Al-Cu alloys, Aachen, Shaker Verlag Aachen (Modeling of casting, welding, and advanced solidification processes, IX), p. 18

Cammer, K., 1995. Aluminium-Taschenbuch. Band 1: Grundlagen und Werkstoffe. 15. Aufl., Aluminium-Verlag, Düsseldorf

Gouffé, A., 1945. Corrections d'ouverture des corps-noirs artificiels compte tenu des diffusions multiples internes, Revue D'Optique Théorique et Instrumentale 24 1-3, p. 1

Hagenlocher, C., Fetzer, F., Weller, D., Weber, R., Graf, T., 2019. Explicit analytical expressions for the influence of welding parameters on the grain structure of laser beam welds in aluminium alloys, Materials & Design 174, p. 107791

Hagenlocher, C., Seibold, M., Weber, R., Graf, T., 2018. Modulation of the local grain structure in laser beam welds to inhibit the propagation of centerline hot cracks, Procedia CIRP 74, p. 434

Hagenlocher, C., Weller, D., Weber, R., Graf, T., 2019. Reduction of the Hot Cracking Susceptibility of Laser Beam Welds in AlMgSi Alloys by Increasing the Amount of Grain Boundaries, Science and Technology of Welding and Joining 24 4, p. 313

Heller, K., Kessler, S., Dorsch, F., Berger, P., Graf, T., 2017. Analytical description of the surface temperature for the characterization of laser welding processes, International Journal of Heat and Mass Transfer 106, p. 958

Kou, S., 2003. Welding Metallurgy. 2. Aufl., John Wiley & Sons, Hoboken

Kurz, W., Fisher, D. J. D., 1986. Fundamentals of Solidification, Trans Tech Publications

Rosenthal, D., 1946. The Theory of Moving Sources of Heat and Its Application of Metal Treatments, Transactions of ASME 68, p. 849

Thijs, L., Kempen, K., Kruth, J.-P., van Humbeeck, J., 2013. Fine-structured aluminium products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder, Acta Materialia 61 5, p. 1809

Vončina, M., Mrvar, P., MEDVED, J., 2006. Thermodynamic Analysis of AlSi10Mg Alloy Termodinamična analiza zlitine AlSi10Mg, RMZ-Materials and Geoenvironment 52 3, p. 621

Wyrzykowski, J. W., Grabski, M. W., 1986. The Hall‐Petch relation in aluminium and its dependence on the grain boundary structure, Philosophical Magazine A 53 4, p. 505