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Laser Deep Penetration Welding of an Aluminum Alloy with Simultaneously Applied Vibrations

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Abstract In aluminum welding, the grain structure of produced seams is an essential factor with respect to the seam properties. In the casting technology the effect of mechanical vibrations on the grain growth during the solidification of liquid metals is known as a refinement method. In this paper, the transferability of this approach from comparatively long-time processes in the field of casting to the short-time process of laser deep penetration welding is investigated. Therefore, specimens were sinusoidal vibrated with frequencies up to 4 kHz during bead-on-plate full-penetration welding experiments. The resulting grain size was determined by applying the circular intercept procedure on the center of a cross-section micrograph of each weld. The results show that grain refinement is in general achievable by mechanical vibrations in the audible frequency range during laser full penetration keyhole welding of the aluminum alloy EN AW-5083.

Keywords Laser welding · Deep penetration welding · Aluminum · Grain refinement · Hybrid process

Introduction and State of Research

In laser deep penetration welding a characteristic vapor capillary is generated due to a high intensity of the laser beam. This vapor capillary, the so called keyhole, offers the opportunity to produce deep weld seams with high aspect ratios along with

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comparatively high energy efficiency due to multiple reflections in the keyhole, see e.g. [1]. Thus, the low absorption of aluminum alloy surfaces in case of heat conduction welding with solid state lasers can be increased in laser keyhole welding up to 93% as shown by Kawahito et al. [2]. However, in contrast to heat conduction processes the keyhole itself and the melt pool in deep penetration welding are significantly more dynamic. Optical process emissions of the keyhole can be used for quantifying these dynamics. Thus, Geiger et al. could relate process oscillations of 100 Hz to 600 Hz to melt pool oscillations and frequencies greater than 1000 Hz to keyhole oscillations using a silicon photo diode for observation [3]. These results have been added by correlations of Otto et al. between model calculations and measurements of optical emissions which reveal that frequencies around 3000 Hz are related to keyhole oscillations [4] and by Volpp and Vollertsen who have shown that metal vapor movements above the keyhole with frequencies from 0.7 Hz to 5000 Hz can be observed using a high-speed camera setup [5]. In deep penetration laser welding of aluminum alloys, besides process instabilities resulting in seam defects the hot crack susceptibility, residual stresses, welding distortion as well as the achievable strength are main challenges with regard to the joint properties.

The mechanical and technological properties of materials are mainly determined by the chemical composition and the grain structure. In this context, grain structures with small grain sizes usually show higher tensile and yield strengths. In addition, Cui et al. found for welding that also the hot crack susceptibility during welding of aluminum alloys is reduced due to grain refinement [6].

Referring to Oettel and Schumann, the occurrence of homogeneous nucleation is low in technical solidification processes like welding due to not reaching the required undercooling [7]. Dommaschk mentioned that heterogeneous nucleation results when solid melt components, like nitrides or oxides, are present [8]. Grain refinement methods can be distinguished categorically in chemical-metallurgical and mechanical methods.

Schempp et al. have shown as chemical-metallurgical method that additions of grain refiner Al Ti5B1 (Al: aluminum, Ti: titanium, B: boron) affect the grain size and the hot-cracking susceptibility in full penetration GTA welding (gas tungsten arc welding) of aluminum alloy EN AW-6082 [9]. Titanium contents above 0.05 wt.-% avoid the occurrence of hot cracks. When comparing welds (welding speed of 4.2 mm/s) with titanium additions of 0.03 wt.-% (hot cracking observed) and 0.07 wt.-% (no hot cracking), the mean grain size and the area fraction of equiaxed grains differ from 35 μm to 22 μm and from 84% to 97%, respectively. Thus, comparatively small changes in the grain structure can be decisive regarding the hot cracking phenomena. Tang and Vollertsen showed that the chemical-metallurgical method of implementing titanium and boron particles in aluminum alloys can also be used for grain refinement in laser welding [10]. A mechanical grain refinement was achieved e.g. by Chen et al. who manipulated the melt pool surface [11], by Sakwa et al. with electromagnetic stirring [12] or by Kou and Le with scanning of the arc torch in arc welding [13]. Also ultrasound or mechanical vibration manipulation methods, shown for example by Dommaschk and Hübler [14], belong in this category.

Mechanical vibration methods differ from ultrasound based methods in the used frequency spectrum. Vibration treatments use frequencies in the infrasound (0 Hz to 20 Hz) and the audible sound (20 Hz to 20 kHz), while ultrasound treatments use frequencies in the range between 20 kHz and 100 kHz. Vibration methods can offer oscillation amplitudes in micrometer up to millimeter range; in ultrasound methods amplitudes are typically limited to the low micrometer range.

Investigations on grain refinement effects due to mechanical vibrations have been conducted at first in the field of metal casting. It is not clear yet, which nucleation mechanism is mainly responsible for the grain refinement by vibration. In accordance with the dynamic grain refinement idea nuclei develop under mechanical impact in the melt without the presence of solid particles. Local falling below the solidus temperature due to pressure changes could be the reason for nucleation. In contrast, a so called grain multiplication is achieved by the scattering of solidified grains due to vibration impacts, shocks or fluid flows acting as new nuclei. According to Kou mainly dendrite tips are cut off during that process [15]. Referring to Xu et al. grain refinement is correlated to the increased melt pool flow which induces a stirring of the colder melt close to the melting line with the overheated melt in the melt pool center [16]. The grain growth rate and the nucleation rate are therefore influenced by resulting higher cooling rates.

Dommaschk has concluded that the acceleration is the main factor for grain refinement in casting processes when vibration is applied [8]. Campbell reviewed grain-refinement literature for casting processes and concluded on the basis of his study that grain refinement by vibration application depends on the multiplication product of vibration frequency and amplitude [17]. He found that first grain refinement effects can take place in case of favourable conditions when a threshold of 0.1 mms^{-1} for the parameter product is reached. However, product values above 3 mms^{-1} (determined by a graph) are mentioned for optimum grain refinement behavior. It seems that the thresholds are valid for a wide variety of metals and vibration conditions (amplitudes and frequencies in the ranges from 10^{-7} m to 10^{-2} m and 10^{0} Hz to 10^{5} Hz, respectively).

The knowledge from investigations on casting processes cannot be readily transferred to welding processes and, especially, to laser keyhole processes due to the significantly faster cooling rates. Vibration methods have been tested on different welding processes at different vibration treatments and materials. Most investigations were conducted in the field of arc welding of metallic, often steel, seams. The treatments achieved several positive effects that can be mainly correlated to a grain refinement due to the induced vibrations. Tewari found increased fracture toughness [18] and Pučka and Gliha increased notch impact strength [19]. Hussein et al. confirmed the increase of fracture toughness [20] and more homogeneous distributions of micro phases have been found by Gericke et al. [21]. Xu et al. have shown that vibration treatment also leads to reduced residual stresses, e.g. in flat specimens and welded tubes, and reduced distortion [16]. Aoki et al. found the maximum reduction of residual stresses in their study applying the resonance frequency [22].

When welding aluminum alloys with mechanical impact the following effects were seen. When welding aluminum alloy 7075, reduced hot crack susceptibility due to grain refinement under mechanical vibration treatment at a frequency of 2050 Hz at GTA (gas tungsten arc) welding was found by Balasubramanium [23]. Dai saw a grain refinement of aluminum alloy 7075 at GTA welding when using ultrasound stimulation [24]. Kou and Le achieved a reduced hot crack susceptibility of aluminum alloy 5052 due to grain refinement by GTA welding with arc oscillation [13]. Further, Kou and Le detected grain refinement in GTA welding with arc oscillation of the aluminum alloy

6061 due to heterogeneous nucleation [25]. Using magnetic stirring a grain refinement at GTA welding of aluminum alloys was observed by Pearce and Kerr while a minimum titanium percentage was required [26]. Rao et al. showed that fine equiaxed grains are visible in GTA weld seams of aluminum alloy 2219 when using arc oscillation and AC current pulsing as well as its combination [27].

Purpose

Based on the current state of research, grain refinement is a topic of great interest due to the importance of the grain structure for joint properties in welding. For example, chemical-metallurgical approaches have demonstrated that comparatively small changes in the grain structure can decisively affect the hot cracking susceptibility. However, no investigation on mechanical grain refinement during laser or electron beam deep penetration welding of aluminum alloys in the range of the audible sound (20 Hz to 20 kHz) have been presented. These welding processes feature significant differences concerning the solidification properties compared to other welding techniques as well as to a greater extent to casting processes, like the low energy input per unit length as well as comparatively high welding velocities and high aspect ratios, resulting in high temperature gradients and high nucleation speeds.

The state of research shows that the product of frequency and amplitude of applied vibrations affects the grain refinement behavior in casting processes of aluminum alloys, including amplitudes from the micrometer to the millimeter range and frequencies from a few hertz to several kilohertz. In contrast to casting as well as comparatively slow welding processes, the referred literature points also out that during laser deep penetration welding besides process oscillations in the range from 100 Hz to 600 Hz being related to the melt pool frequencies up to 5000 Hz being induced by keyhole dynamics have been observed. Thus, this study shall characterize the effect of simultaneously applied mechanical vibrations during laser deep penetration welding of an aluminum alloy for a broad range of frequencies.

Methods

Welding Process

Experiments in this paper contain the analysis of specimen vibrations as well as the analysis of the resulting grain structure of weld seams. Welding is conducted in aluminum sheets of 3 mm thickness. A welding velocity of 3.6 m/min and a laser power of 3.1 kW have been applied. A disk laser (TruDisk8002 by Trumpf) with a wavelength of 1030 nm is used. A standard welding head (BEO D70 by Trumpf) contains the collimation lens (200 mm focal length) and the focusing lens (400 mm focal length). Using an optical fiber with a core diameter of 200 μm for beam delivery a nominal focus diameter of 400 μm at a Rayleigh-length of 4.16 mm is applied. The focal position is set to 7 mm underneath the specimen's surface. Argon is used as shielding gas on the upper surface at a flow rate of 17 l/min and helium from the bottom side of the specimen at a flow rate of 4.5 l/min. Welding velocity of the welding optics is achieved by a CNC controlled gantry system.

Vibration Setup

For mechanical vibration of the specimens an electrodynamic shaker (V406 by LDS by Ling Dynamic Systems) is used which is controlled by a digital function generator (33220A by Agilent Technologies Inc.). The amplification of the control signal is realized by a linear power amplifier (PA240 E by Ling Dynamic Systems). A clamping system is installed on top of the shaker including the gas nozzle for the mentioned shielding gas supply. Figure 1 shows the setup. The mass of the specimens has been determined to 0.047 kg as an average of three measured items. Adding the mass of all parts of the clamping system of 0.586 kg and the moving mass of the shaker of 0.200 kg, determined by the producer of the Shaker, the complete moving mass in the experiments is 0.833 kg. With the help of this setup the specimens can be vibrated in vertical direction.

An acceleration sensor (DeltaTron 4519-003 by Brüel & Kjaer, see Fig. 2) measures the acceleration of the specimen. The measuring range regarding the frequencies is from 1 Hz to 220 kHz and regarding the accelerations ± 490 m/s^2. The resonance frequency of the sensor is specified to 62 kHz and the amplitude slope to -1.35/decade. The sensor is applied on the specimen in the center by using a manufacturing wax (Methyl Cyanoacrylat). Without the data wire the mass of the sensor is measured to 1.5 g. In order to avoid influences of the wire mass and wire vibrations, a free hanging wire length of 0.35 m is provided.

Acceleration measurements are conducted without turning on the laser while the vibration frequencies are varied. A transient recorder (2580P by Gould Nicolet) records the measuring signal at a recording frequency of 50 kHz and a recording time of 0.1 s. Evaluation of the recorded data is conducted in MATLAB (TheMathwork). Voltage amplitudes are determined by measurements. Acceleration values are calculated from the voltage amplitudes considering the preset amplification factor. The oscillation amplitudes are calculated using the measured accelerations. Based on the assumption of a harmonic sinusoidal oscillation correlations between the angular frequency ω, the acceleration a and the amplitude s can be drawn (Eq. 1 and eq. 2, see e.g. [28]). For

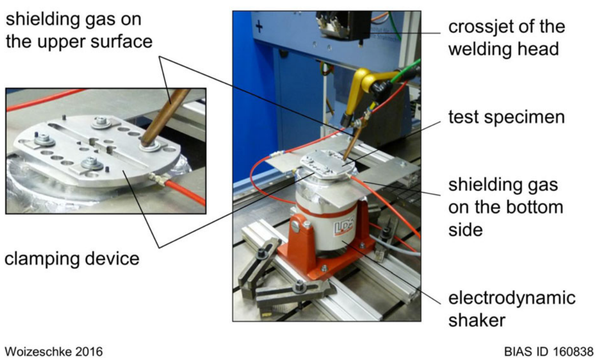

Fig. 1 Experimental setup for investigating mechanical vibrations on laser deep penetration welding

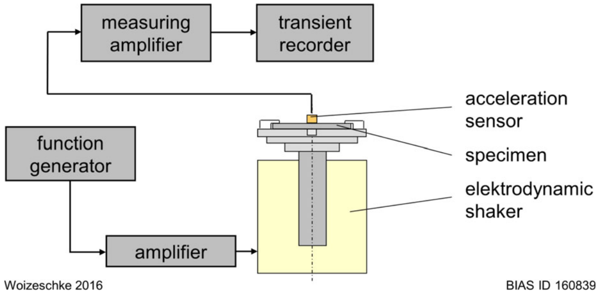

Fig. 2 Principle of the vibration setup

calculating the amplitude the preset frequency f of the function generator and the maximum absolute acceleration value are taken.

$$a + s{\cdot}\omega^2 = 0 \tag{1}$$

$$\omega = 2{\cdot}\pi{\cdot}f \tag{2}$$

Grain Structure Characterization

Full-penetration welds are conducted in order to investigate the impacts of mechanical vibrations on the resulting grain structure. Cross-section polishes are taken at the weld center and electrolytically etched (based on methods of Barker). For the analysis of the grain structure average grain sizes are determined using the circular intercept procedure, see for example [29]. Using this method, the average grain diameter is calculated by the ratio of a line length in the cross section frame and the number of grain boundaries cut by that line. A direction-independent measurement is guaranteed by drawing three concentric circles of diameters 160 μm, 300 μm and 440 μm and averaging the results. This measurement is repeated at three positions in the seam center according to Fig. 3. The average grain size value from all nine circles is called the center grain diameter of the specimen.

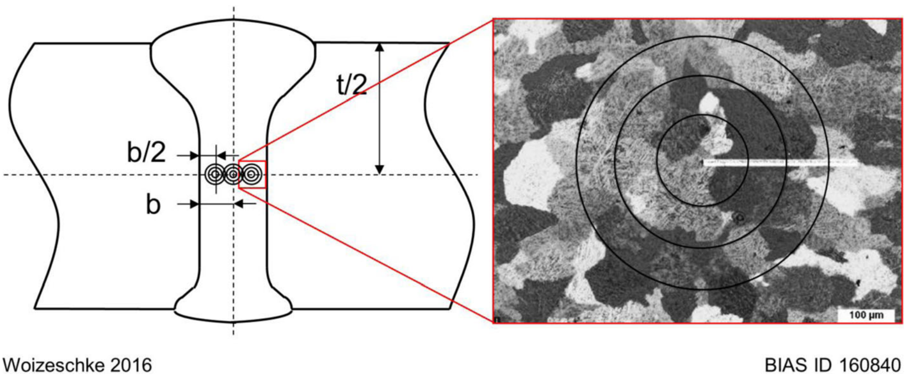

Fig. 3 Procedure of the determination of the center grain diameter

Material

In this study, investigations on the influence of mechanical vibrations during laser deep penetration welding of aluminum alloy EN AW-5083 are conducted. The used material, H111 treated, is slightly strain-hardened (less than H11) during subsequent operations such as stretching or levelling after annealing.

Program

The welding experiments are conducted in flat position. Bead-on-plate full-penetration welds of 100 mm length are produced. Weld seams are positioned in the center of the specimen width. Specimen width and length are 50 mm and 120 mm, respectively. The used vibration frequencies are in the range from 60 Hz to 4 kHz. The vibration is a directed oscillation perpendicular to the specimen surface (z-direction) in order to avoid a spatial keyhole oscillation in the x-y-plane. A sinusoidal signal is used as control signal. Vibration starts and continues 5 s before/after the welding process. In addition, non-vibrated welding is carried out as reference.

Results

Figure 4 shows the maximum measured acceleration values depending on the vibration frequencies at sinusoidal excitation and the calculated oscillation amplitudes. The determined acceleration values are in the range between 76 m/s^2 and 102 m/s^2 for frequencies under 2 kHz. At a frequency of 4 kHz the acceleration significantly increases to 473 m/s^2. On the basis of these acceleration values the amplitude as a function of the oscillation frequency is determined by Eq. 1. The amplitude decreases from 257 μm at a frequency of 100 Hz to less than 1 μm for frequencies over 2 kHz. In

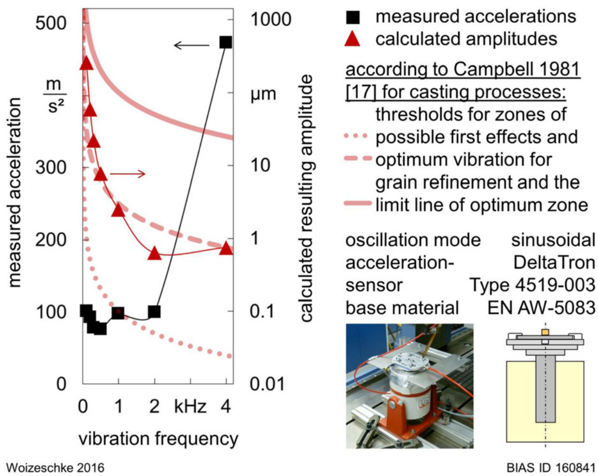

Fig. 4 Measured acceleration and calculated amplitude values as functions of the oscillation frequency for the applied setup and thresholds as well as a limit line for the product of frequency and amplitude regarding the resulting grain refinement according to [17] for casting processes

addition, the thresholds of the product of frequency and amplitude, which Campbell has concluded by a literature review [17] for vibration applications in casting processes, for zones of (1) possible grain refinement effects under favourable conditions and (2) optimum vibration for grain refinement as well as (3) the limit line of the optimum parameter zone are integrated. The comparison shows that the applied vibration in this study is always in the transition range between the two zones.

In this study, the average grain diameter in the center of each seam is determined using a circular intercept procedure in order to analyze the influence of the vibration frequency by the so called center grain diameter as characteristic value. Altogether, center grain diameters of 37 seams are determined at frequencies between 60 Hz and 4 kHz as well as without any vibration of the specimen. The measured center grain diameters vary in the range from 37 μm to 77 μm. The distribution of all individual values over the investigated frequency range (Fig. 5a) shows a slight decrease when using a linear regression. However, the results include erratic changes of the center grain diameter also between frequency values in juxtaposition with each other. The mean center grain diameter for the non-vibrated reference case is determined to 62 μm ± 12 μm.

In order to compare different frequency ranges, the individual values are additionally averaged in frequency categories of 1 kHz, see Fig. 5b. In comparison with the average of the non-vibrated weld seams, a tendency to smaller grain sizes in the seam center when applying vibrations is also visible here. The frequency range between 2 kHz and 3 kHz offers the smallest average of the center grain diameter of 48 μm ± 5 μm. In addition, the variance between the included five individual values is smaller than in the other frequency categories.

The analysis in Fig. 5 deals with the local grain structure in the seam center. In order to investigate the grain refinement behavior within the complete cross-section of laser welded seams with simultaneously applied specimen vibrations three exemplary seam cross-sections are chosen, see Fig. 6. Figure 6a shows the cross-section of a non-vibrated reference weld seam. The overall grain size is bigger compared to the one of the base material. The grain structure mainly consists of columnar grains of short and thick form. The growth direction of the columnar grains is mainly perpendicular to the

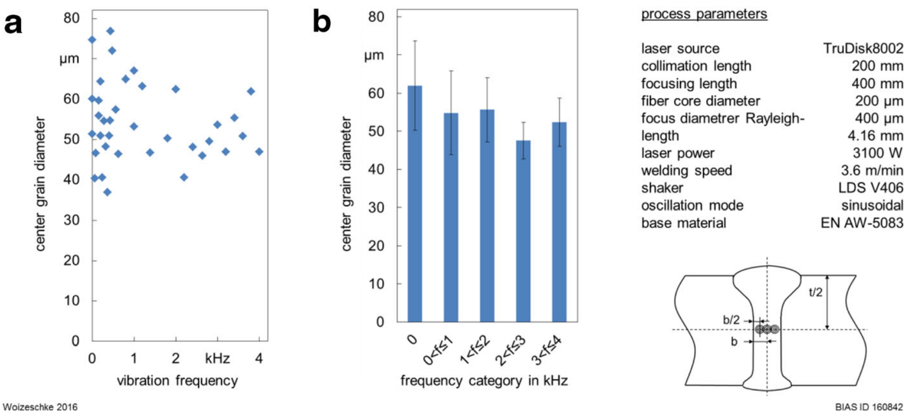

Fig. 5 (**a**) Determined center grain diameters for different frequencies as well as for a non-vibrated reference; (**b**) averaged center grain diameter values for frequency categories of 1 kHz

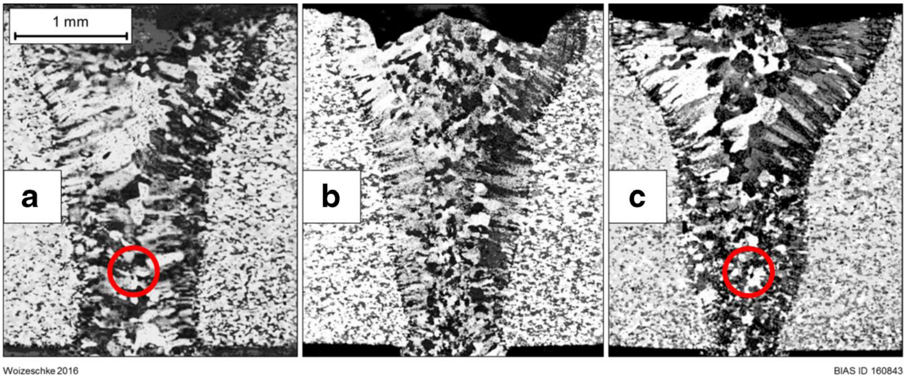

Fig. 6 Seam cross section micrographs: (**a**) non-vibrated; (**b**) vibrated during welding with 240 Hz; (**c**) vibrated during welding with 2200 Hz (*red circles* illustrate additional measurements of average grain diameters in the lower seam part)

local fusion line orientation but in general more horizontal than vertical. In the seam center a field of big equiaxed or axial grains is visible. The weld seam width decreases from the upper to the lower seam part in case of all shown cross-sections in Fig. 6.

In comparison with the non-vibrated one, the seams of the specimens being vibrated during welding are thinner at the seam root and partially wider at the seam top, see Fig. 6c. Moreover, an increased undercut of the seam is partially observed, see Fig. 6b. Figure 6b shows the seam shape and the grain structure after harmonic vibration during welding with 240 Hz and Fig. 6c with 2200 Hz. Except of an epitaxial zone the inner grain structure of the 240 Hz sample is finer and consists of smaller equiaxed grains in comparison with the non-vibrated one. In contrast to both the non-vibrated sample (Fig. 6a) and the 240 Hz one (Fig. 6b), the grain structure within the cross-section of the 2200 Hz seam (Fig. 6c) differs significantly in depth direction. While the upper half of the seam mainly consists of columnar grains which are perpendicularly directed to the local fusion line orientation and seem to be partially coarser than in the reference seam, the lower half consists of equiaxed considerably finer grains. In order to determine the extent of this locally limited grain refinement, additional average grain diameters are measured for the lower halves of the seams in Fig. 6a and c. The measurement locations are illustrated in the figures by red circles. In doing so, values of 55 μm and 32 μm have been determined for the non-vibrated and the 2200 Hz sample, respectively. In comparison with the cross-section of 240 Hz, the 2200 Hz specimen shows also a significantly reduced epitaxial zone in the lower half of the seam.

Discussion

Although the spreading width of the results a tendency towards producing grain refinement by mechanical vibrations during laser deep penetration welding of the aluminum alloy EN AW-5083 can be confirmed by this study. Thus, the results of this study are not in conflict with the state of research dealing with other materials, vibration sources and welding processes with slower solidification speeds. In addition, the results fit in principle with the aforementioned conclusions of Campbell [17] about the thresholds of the product of oscillation frequency and amplitude regarding resulting grain refinement effects which he stated for casting processes. According to these thresholds, the applied vibrations in this study should result in grain refinement under favourable conditions but not in optimum grain refinement because the applied parameter sets are between the two mentioned zones, see Fig. 4. Thus, it is possible that the wide spreading of the achieved refinement results is caused by small changes in the process conditions because the level of the product of frequency and amplitude is too low for reliable significant grain refinement in this study.

In general, different factors affect the measured center grain diameter of a seam. Each factor could be more or less responsible for the spreading width of the grain size values over the investigated frequency range, see Fig. 5a. First, specific interactions between induced mechanical vibrations with the melt pool as well as the keyhole of the welding process could cause erratic changes of the grain refinement behavior also between frequency values in juxtaposition with each other. Geiger et al. showed that the oscillations of both melt pool and keyhole cover the investigated frequency range of the vibrations in this study [3]. Therefore, a potential stimulation of, for example, natural frequencies might influence the effect of the outer vibration on the process behavior and the resulting grain structure at a specific frequency value.

Second, material and process tolerances can affect seam shapes and grain structures by seam-to-seam variances or changes along the seam length. Seam-to-seam variances at constant parameters are possible due to process tolerances as observed, for example, in case of the non-vibrated reference weld seams with a standard deviation of 12 μm for the determined center grain diameters. Variations of the seam shape in longitudinal direction of a seam to a greater or lesser extent and more or less regular are not considered by a single cross-section measurement per seam. For example, seam surfaces in welding can offer typical bead ripples.

Third, the measurement of the center grain diameter cannot accurately describe the grain refinement behavior if the grain structure is location-dependent and differs in depth direction of the seam. For example, the seam cross-section in Fig. 6c shows significant differences in the grain structure between the upper and the lower seam halves. The grain structure of the upper half of the seam being vibrated with 2200 Hz does not differ significantly from the non-vibrated one in Fig. 6a while the grain structure of the lower half is considerably finer with 32 μm in comparison to 55 μm. Such an extent of grain size change could significantly affect the hot cracking susceptibility in welding of EN AW-6xxx aluminum alloys, see for example [9]. Specimens, as shown in Fig. 6c, with location-dependent grain refinement offer transition zones between affected and non-affected seam parts. In this study, this transition is partially located near the seam center at which the grain size is characterized by the center grain diameter. As a result, small differences in the position of this transition can result in considerable differences in the measured center grain diameter value.

In addition, the lowest average center grain diameter for the frequency category for individual values between 2 kHz and 3 kHz indicates that oscillation amplitudes of 1 μm can apparently still affect the grain structure which confirms results in the field of casting processes (see e.g. [17]). Moreover, the affected seam shape and the partially observed grain coarsening in the upper seam part suggest that the applied mechanical vibrations can change the fluid flow in the melt pool.

Conclusion

The presented study shows that grain refinement is in general achievable by mechanical vibrations in the audible frequency range during laser full penetration keyhole welding of the aluminum alloy EN AW-5083. This knowledge extends the state of research in grain refinement by applied vibrations for laser welding with its high solidification speeds. The investigations in this paper reveal that the grain refinement can be location-dependent along the seam depth correlating with seam width variations. The vibration approach offers potential for future application developments if a significant grain refinement can be reliably achieved within the complete seam.

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