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INFLUENCE OF SURFACE ROUGHNESS ON SELECTED GEOMETRIC CHARACTERISTICS OF LASER BEAM WELDED JOINTS OF AW 2099 ALLOY

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Abstract

Al-Li alloys are used in various industries owing to their good mechanical and physical properties. However, one of the limiting factors of welding the aluminium alloys by laser beam is the high reflectivity of the beam and thus the reduced efficiency of the laser. Reduction of reflectivity can be achieved by increasing the surface roughness, which may have a beneficial effect on the absorption of the laser, resulting into affecting the weld bead dimensions. The paper deals with the analysis of the influence of surface roughness of welded materials on geometry of welded joints. Specimens of AW 2099 alloy 2099 with a thickness of 3 mm were milled to achieve different levels of roughness, and then laser welded. Characteristic dimensions of the welds (weld surface/root width) were measured. The obtained data were statistically analysed using the ANOVA method, in order to assess statistical significance of the influence of individual roughness parameters on the geometric characteristics of welds. The results of the analysis showed that, within the monitored range and surface roughness parameters, only the influence of roughness parameter Rq, Rz on the weld root width can be considered statistically significant.

Key words

Laser welding, AW 2099, geometric characteristics, ANOVA

INTRODUCTION

Lithium is the lightest known metal element widely used in metallurgy. Lithium is an excellent alloying element in aluminium for several reasons. With every 1% addition of lithium, the alloy density decreases by about 3 %, but the elastic modulus increases approximately by 6%, which is due to precipitation hardening in aluminium. Owing to the density reduction, the less material is needed and the total weight of component can be decreased. Because of these properties, aluminium alloys have found application in many industries, especially in the aerospace industry (Schlatter 2013, Martin 1998).

On the other hand, aluminium alloys are known for their high laser beam reflectivity, which reduces the amount of energy absorbed during welding. One of the significant factors affecting the energy absorption is the material´s surface roughness. This parameter affects the input costs of production and also laser processing parameters, and thus the price of the entire production process (Obeidi et al. 2019).

The influence of material surface roughness on laser beam absorption has been discussed by several authors. In their study, Arata and Miyamoto examined the CO_2 laser absorptivity by different metals (stainless steel AISI-304, aluminium, iron) of various surface roughness and setups (butt joint, bead on plate). It was noted that absorption level had a tendency to increase with the surface roughness of the joint edge; however, when the surface melts, the absorption decreases to a constant value, 13% for AISI-304, 3% for aluminium and 5% for iron (Arata and Miyamoto 1972).

Covelli et al. performed analysis of CO_2 laser beam welding of butt joints of stainless steel with different edge surface roughnesses obtained by different machining methods. The tests showed that the properties of the welds were not affected by the surface morphology of the joint edge (Covelli et al. 1988).

In their study, Sokolov et. al. investigated the influence of joint edge surface roughness on weld quality and penetration depth. The characteristics were investigated on welded samples of two low-alloyed steels, S355 and St 3, of 20 mm in thickness with various joint edge surface roughness levels in butt joint configuration. They found that absorption of structural steel in butt-joint laser welding showed a significant dependence on the edge surface roughness at laser beam power more than 10 kW. The results show that, within the range Ra = 1.6 to 8 μm, the maximum penetration depths were achieved at a roughness level of Ra = 6.3 μm (Sokolov et al. 2012).

Obeidi et al. investigated the effect of surface roughness on the melt pool dimensions for laser processing of stainless steel and aluminium. Their study showed that the increased surface roughness leads to a considerable increase in the melt pool, which indicates an increase in the laser absorption. The correlation between the melt pool dimensions and the surface roughness is an almost linear relationship (Obeidi et al. 2012).

The goal of the experiment described in the current paper was to analyse the influence of Al-Li alloy surface roughness on the characteristic dimensions of the laser beam welded joints.

MATERIALS AND THE METHODOLOGY OF EXPERIMENT

An aluminium-lithium alloy AW2099 with a thickness of 3 mm was used as an experimental material.

The surface of the material was milled at 12 spots of different milling parameters in order to achieve different levels of roughness. Then the surface roughness parameters (Ra, Rq, Rz) were measured. The most commonly used parameter of surface roughness (Ra) actually reflects the mean absolute value of the deviations forming the profile. The Ra value therefore cannot be quoted on the profile, since it is a mathematically determined value. Therefore, the profiles of different shape and different height specifications may show a similar or the same Ra value.

For better assessment of the profile, it is necessary to supplement this parameter with additional roughness characteristics, namely Rq and Rz (Görög, Samardžiová 2016).

During milling, after removing 0.5 mm of the material thickness, the final thickness of the samples was 2.5 mm. Figure 1 shows the milled material with the labelled samples.

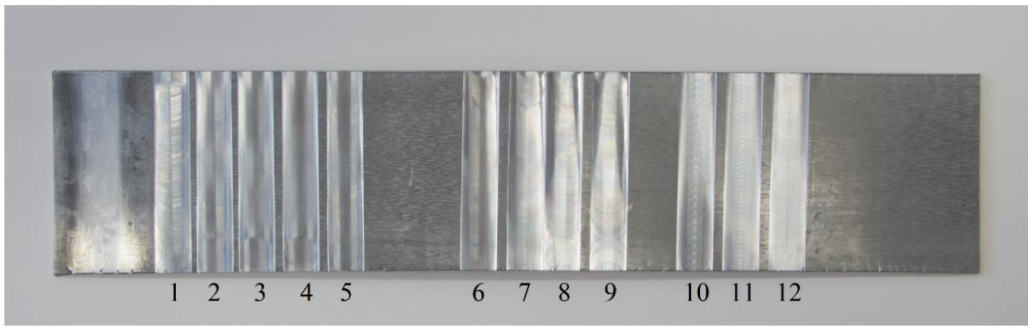


Figure 1 *Milled material*

Milling parameters and obtained surface roughness of the material are listed in Table 1.

Table 1 Milling parameters and obtained surface roughness

Sample	**a_p [mm]**	**v_c [m·min^{-1}]**	**n [rpm]**	**f_z [mm]**	**v_f [mm·min^{-1}]**	**R_a [µm]**	**R_q [µm]**	**R_z [µm]**
1	0.5	500	7958	0.01	318	0.752	0.894	4.121
2	0.5	500	7958	0.1	3183	5.926	6.981	26.037
3	0.5	500	7958	0.15	4775	6.922	8.067	30.741
4	0.5	500	7958	0.2	6366	9.124	10.837	42.128
5	0.5	500	7958	0.05	1592	3.565	4.629	19.000
6	0.5	500	7958	0.083	2642	5.558	6.897	25.358
7	0.5	500	7958	0.083	2642	8.812	10.437	36.426
8	0.5	500	7958	0.045	1432	5.689	6.46	22.105
9	0.5	500	7958	0.04	1273	5.093	5.780	20.083
10	0.5	500	7958	0.22	7003	11.514	14.957	61.706
11	0.5	500	7958	0.24	7640	10.883	13.495	54.131
12	0.5	500	7958	0.175	5571	14.957	55.829	55.829

Legend: **a_p** − depth of cut, **v_c** − cutting speed, **n** − revolutions per minute, **f_z** − feed per tooth, **v_f** − feed speed, **Ra** − arithmetical mean deviation of the assessed profile, **Rq** − root mean square deviation of the assessed profile **Rz** − maximum height of the profile

After preparing the samples of different surface roughness, beads on plate welds were made. In an effort to eliminate inaccuracies associated with the weld edge preparation and the setup of the materials to be welded, the bead on plate was chosen instead of butt welding. Welding parameters are listed in Table 2, while the weld cross-section appearance is illustrated in Figure 2.

Table 2 Welding parameters	
Laser power [W]	1700
Welding speed [mm·s^{-1}]	15
Shielding gas flow (argon) [l·min^{-1}]	30
Focal position [mm]	0

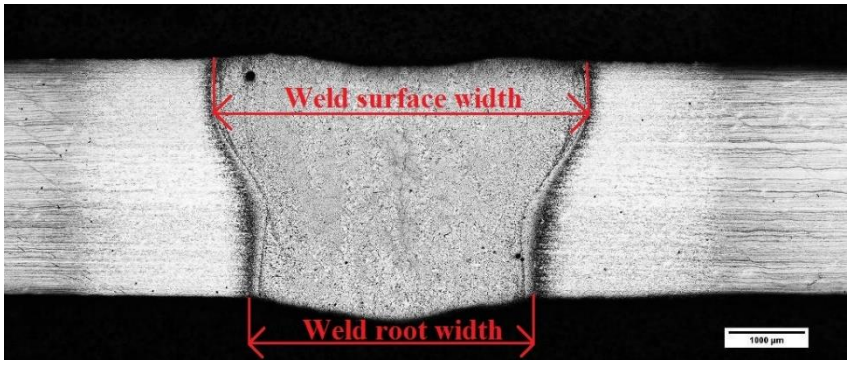


Figure 2 *Weld cross section appearance*

After welding, the widths of the surface and the root of welds were measured using a Dino-Lite digital microscope. Six measurements were performed on each weld, where the individual measured points were 10 mm apart. Figure 3 shows the principle of measurement.

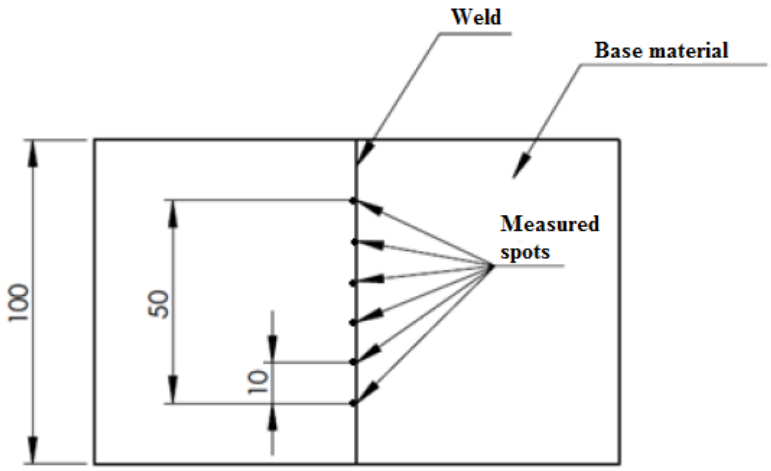


Figure 3 *Scheme of measuring the width of surface and root of the weld*

The mechanically machined sample is shown in Figure 4. The shape of the surface and root of the weld bead of all samples were regular, no defects were visually identified, and the spatter of the weld metal was minimal.

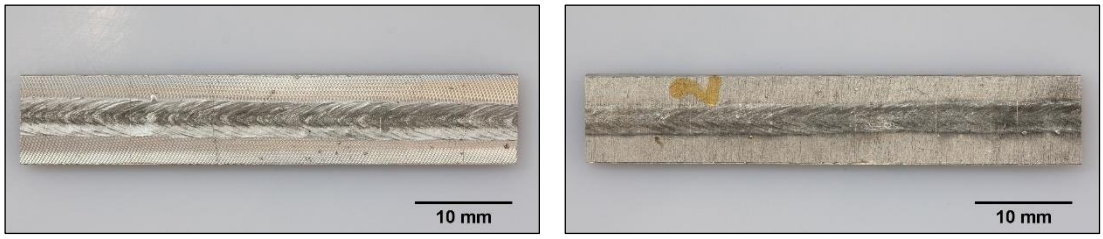


Figure 4 *Appearance of the weld bead: left – surface, right – root*

RESULTS AND DISCUSSION

Correlation between weld surface width and surface roughness

After measuring the geometric dimensions of the welds, statistical analysis of variance (ANOVA) was performed in the GraphPad Prism 8 software package. Table 3 lists dimensions of the weld surface depending on the surface roughness of sample.

Table 3 Weld surface width depending on surface roughness

Sample	Ra [µm]	Rq [µm]	Rz [µm]	Weld surface width [mm]						
				A	B	C	D	E	F	Average
1	0.752	0.894	4.121	4.46	4.75	4.61	4.77	4.63	4.39	**4.60**
2	5.926	6.981	26.037	4.29	4.41	4.41	3.88	4.26	4.08	**4.22**
3	6.922	8.067	30.741	4.21	3.93	4.06	3.84	4.15	3.82	**4.00**
4	9.124	10.837	42.128	4.41	4.31	4.35	4.38	4.41	4.02	**4.31**
5	3.565	4.629	19.000	4.12	4.30	4.34	4.45	4.29	4.09	**4.27**
6	5.858	6.897	25.358	4.29	4.18	4.27	4.38	4.35	4.34	**4.30**
7	8.812	10.437	36.426	4.72	4.98	4.75	4.93	4.45	4.10	**4.66**
8	5.689	6.460	22.105	4.39	4.39	4.70	4.30	4.51	4.17	**4.41**
9	5.093	5.780	20.083	4.47	4.29	4.22	4.27	4.42	4.35	**4.34**
10	11.514	14.957	61.706	4.39	4.25	4.45	4.46	4.39	4.25	**4.37**
11	10.883	13.495	54.131	4.29	4.34	4.50	4.47	4.49	4.34	**4.41**
12	14.797	16.946	55.829	4.38	4.33	4.37	4.45	4.50	4.50	**4.42**

Table 4 lists evaluation of statistical analysis of the correlation between the weld surface width and the material roughness.

Table 4 Statistical analysis of the correlation between weld surface width and surface roughness

Surface roughness	Ra	Rq	Rz
P value	0.4072	0.8872	0.9113
Deviation from zero ?	Not Significant	Not Significant	Not Significant

The P value of the result obtained from the sample is the probability that the observed dependence between the variables is entirely random, and thus this dependence does not actually exist. The higher level of significance, the lesser the observed dependence obtained from the examined data can be expected in the whole basic set. Thus, the observed significance value of 0.4072 (Table 3, Ra value) indicates that there is at most a 40.72% probability that the relationship between the variables found in the sample is entirely random. A result is considered statistically significant if the P value is less than 0.05. Table 3 suggests that none of the significance levels (P value) was less than 0.05. The obtained results (Table 3) show that the effect of surface roughness on width of weld surface is not statistically significant. This means that the results obtained from the examined data cannot be generalized to the entire basic set.

Graphical correlations between weld surface width and surface roughness is shown in Figure 5.

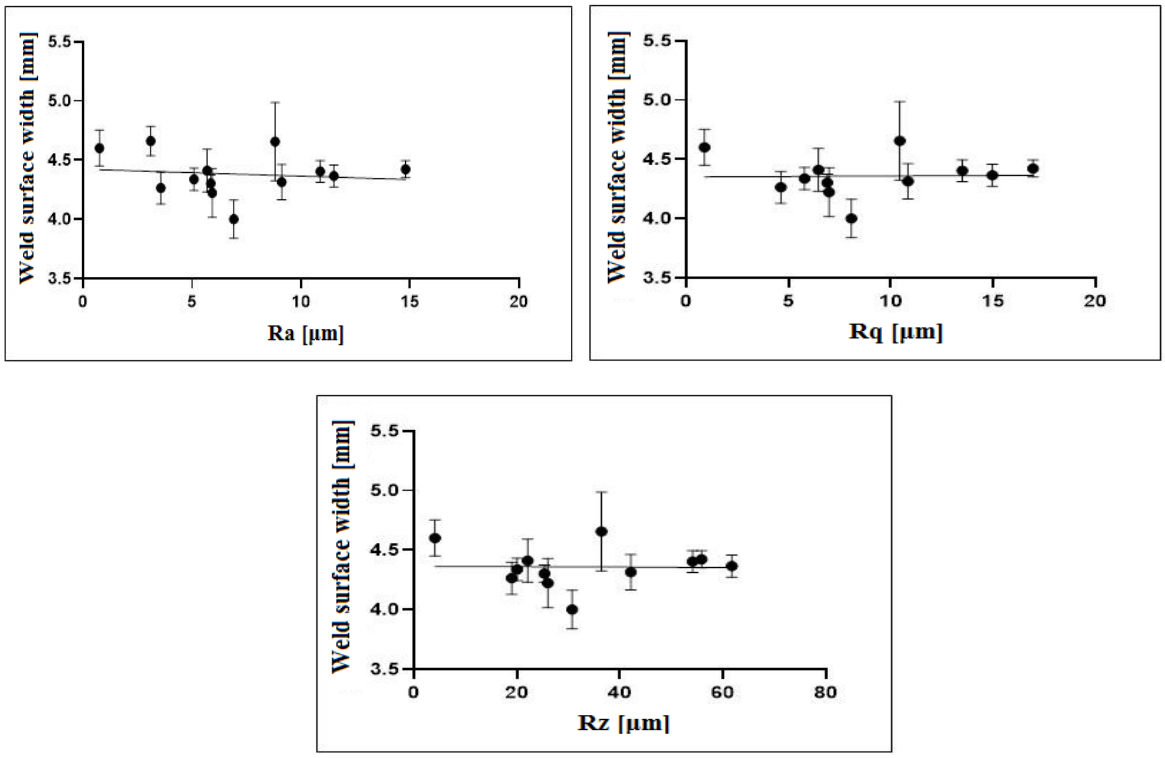


Figure 5 *Graphical dependence of weld surface width on surface roughness*

The data in Figure 5 are presented as a mean ± standard deviation. It is obvious that the measured data show a significant variance in values, which proved their statistical evaluation as insignificant.

Correlation between weld root width and surface roughness

Table 5 lists dimensions of the weld root depending on the surface roughness of sample.

Table 5 Weld root width depending on surface roughness

Sample	Ra [µm]	Rq [µm]	Rz [µm]	Weld root width [mm]						
				A	B	C	D	E	F	Average
brush	3.103	–	–	3.69	4.10	3.81	3.25	3.52	3.48	3.64
1	0.752	0.894	4.121	3.50	3.55	3.44	3.45	3.57	3.65	3.53
2	5.926	6.981	26.037	3.60	3.41	3.65	3.37	3.56	3.57	3.53
3	6.922	8.067	30.741	3.45	3.35	3.45	3.41	3.53	3.40	3.43
4	9.124	10.837	42.128	3.63	3.61	3.78	3.70	3.56	3.68	3.66
5	3.565	4.629	19.000	3.56	3.98	3.62	3.87	3.48	3.72	3.71
6	5.858	6.897	25.358	3.49	3.48	3.54	3.50	3.57	3.48	3.51
7	8.812	10.437	36.426	3.36	3.40	3.53	3.46	3.54	3.38	3.45
8	5.689	6.460	22.105	3.45	3.57	3.64	3.41	3.61	3.49	3.53
9	5.093	5.780	20.083	3.45	3.40	3.42	3.35	3.56	3.50	3.45
10	11.514	14.957	61.706	3.44	3.43	3.42	3.49	3.78	3.54	3.52
11	10.883	13.495	54.131	3.48	3.45	3.36	3.40	3.60	3.48	3.46
12	14.797	16.946	55.829	3.43	3.62	3.52	3.60	3.65	3.85	3.61

Table 6 lists evaluation of statistical analysis of the correlation between weld root width and material roughness.

Table 6 Statistical analysis of the correlation between weld surface width and surface roughness			
Surface roughness	**Ra**	**Rq**	**Rz**
P value	0.624	0.0011	0.0016
Deviation from zero ?	Not Significant	Not Significant	Not Significant

Table 6 indicates that the significance level (P value) for the Ra (arithmetical mean deviation of the assessed profile) was not less than 0.05. This means the effect of Ra roughness parameter on the weld root width value is not statistically significant. In the case of Rq (root mean square deviation of the assessed profile) and Rz (maximum height of the profile), the resulting P value was less than 0.05. The influence of the Rq and Rz roughness is statistically significant, and thus the obtained result is valid for the entire basic set.
Graphical correlations between weld root width and surface roughness is shown in Figure 6.

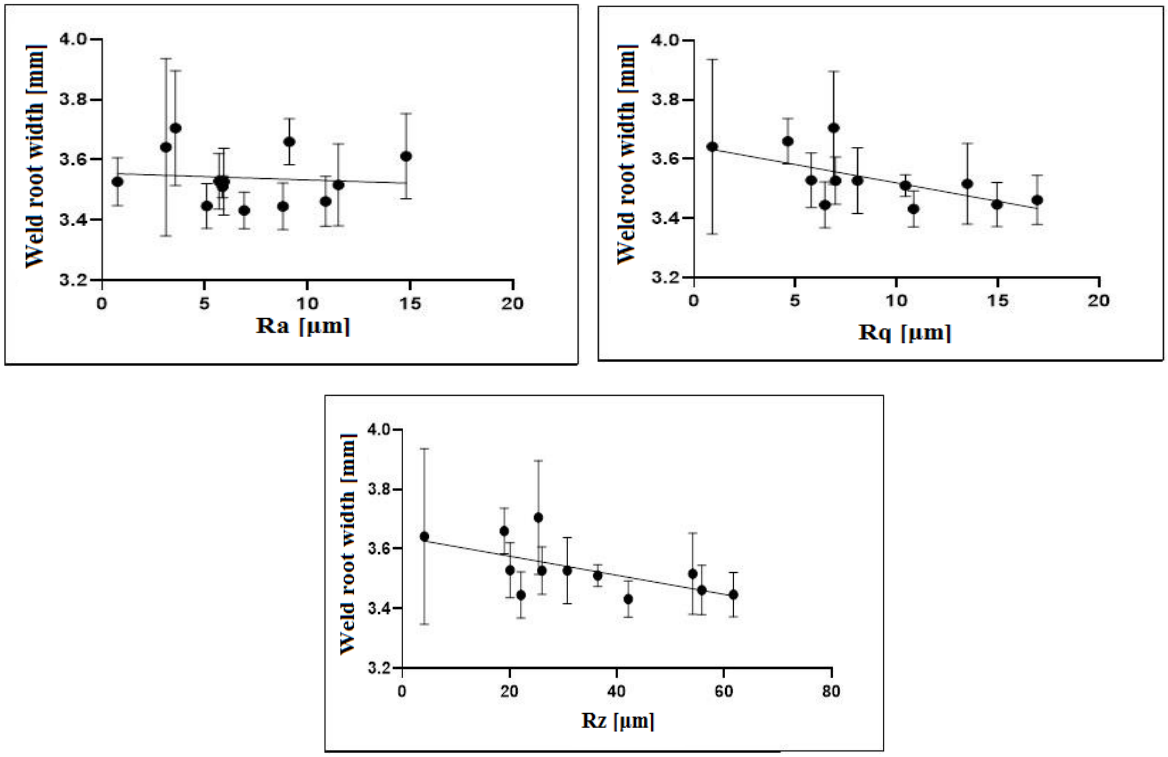


Figure 6 *Graphical dependence of weld root width on surface roughness*

In the case of Rq and Rz surface roughness parameters, statistical analysis showed these two values as statistically significant, but, owing to the large variance of the data, the correlation coefficient was small (0.1419 and 0.1334 respectively), and therefore the exact dependence of the weld root width on the surface roughness of the welded material could not be determined. These findings are contrary to the results of the authors (Obeidi et al. 2012, Sokolov et al. 2012) who found the direct dependence between surface roughness and weld pool dimensions as well as depth penetration. The differences may be caused by a laser type used (CO_2 vs Yb:YAG disc laser), different welding regime (pulsed vs continuous) as well as diverse power beam density.

CONCLUSION

Statistical analysis of variance (ANOVA) did not confirm the effect of any roughness parameter on the width of the weld surface within the examined range (Ra=0.752 to 14.797 μm, Rq=0.894 to 16.946 μm and Rz= 4.121 to 55.829 μm). The significance level indicating the probability of randomness of correlation between weld surface width and surface roughness was 0.4072 for Ra, 0.8872 for Rq and 0.9113 for Rz. The result considered statistically significant exhibits a P value of less than 0.05. In other words, there is a 40.72% probability for Ra, an 88.72% probability for Rq and a 91.13% probability for Rz that the relationship between the given roughness parameters and the weld surface width is entirely random, and therefore the surface roughness has no significant effect on the weld surface width.

The similar results were obtained from the statistical analysis of the correlation between the weld root width and the surface roughness parameter Ra. The significance level has a value of 0.624, and thus there is a 62.4% probability that the dependence between the monitored parameters is entirely random. The Ra parameter has no effect on the weld root width.

On the contrary, for the roughness parameter Rq and Rz, the significance level was 0.0011 and 0.0016 respectively. The found levels of significance were less than 0.05, which indicates that the effects of the roughness parameters Rq and Rz were statistically significant, thus proving/confirming the dependence of the weld root width on the material roughness.
The obtained results are contradictory to the findings of the other authors, and therefore further research might be considered.

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