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AA6082-T6 FRICTION STIR WELDED T-JOINTS OPTIMIZATION

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ABSTRACT

The increasing use of aluminium alloys in transportation industry such as railways, shipbuilding and aeronautics, promotes the development of more efficient and reliable welding processes. Friction Stir Welding is a prominent solid-state joining technology that arise has a possible reliable welding solution. Optimized process parameters are not regularly used in previous studies found in the literature, in particular to weld T-joints, which difficult the process industrial application. This study is focused on the optimization of friction stir welded aluminium alloy T-joints using the Taguchi method. The most influent welding parameters and best parameters combination to achieve improved joint tensile properties were determined.

Keywords: T-joints, Friction stir welding, optimization, Taguchi.

INTRODUCTION

The T-joint is an important geometry when improved inertia and strength of thin skins without significant weight increase are needed. This geometry is commonly used in the reinforcement of aircraft fuselages, railway cars and many other applications where the weight of the structure is of particular importance [1-5].

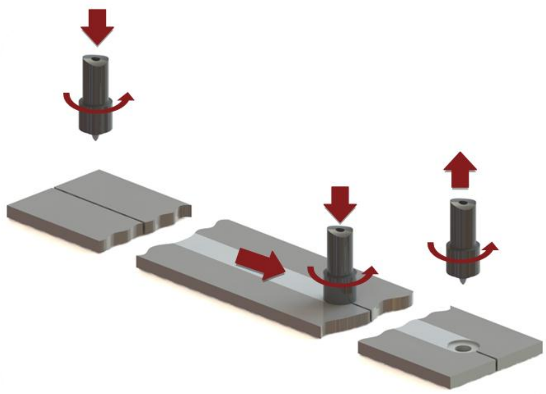


Fig. 1 - Schematic diagram of the FSW process.

T-joints of aluminum alloys welded by fusion techniques present, due to high temperatures achieved during welding, high residual stresses and significant distortion that are difficult to avoid without time-consuming and costly additional operations [2, 6]. Friction stir welding (FSW) arised as a possible solution to replace conventional fusion welding processes to fabricate T-joints of aluminum alloys. This process is a solid-state joining technology where a special tool in rotation is inserted into the work pieces faying surfaces and transverse along the joint line providing a complex stirring of the material. When compared with fusion techniques FSW presents improved surface finishing, absence of porosity, absence of segregation or hot cracking and no need for consumables. Nevertheless, it is still necessary the analysis of the parameters interactions and determine their influence in the joint mechanical strength [1-3, 6, 7].

Only a few studies about T-joints welded by FSW may be found in the literature. Aluminum alloys T-joints welded by FSW were analysed by Fratini et al. [1-3]. In these studies was attempt to determinate the specific process parameters to obtain sound AA6082-T6 FSW T-joints, evaluating their performance through bending tests. Results were compared with metal inert gas (MIG) welds and extruded T-parts [6], and also microstructural and mechanical properties were evaluated [2]. Material flow in FSW of AA2024-T4 T-joints were investigated by numerical simulations, and experiments where a thin sheet of copper placed between the skin and the stringer was utilized [3]. The influence of material characteristic on FSW plastomechanics in AA2024-T4 and AA6082-T6 T-joints was studied by Fratini et al. [1]. Erbslöh et al. [4], studied the detection of weld defects in 4 mm thick AA6013-T4 FSW T-joints. Acerra et al. [5], presents an industrial case study of aeronautical AA2024-T4 and AA7075-T6 dissimilar T-shaped parts joined by FSW. Distributions and mechanisms of defects formation in AA6061-T4 FSW T-joints, in three different combination of skins and stringers, were investigated by Cui et al. [7]. FSW AA6056 and AA7075 dissimilar T-joints residual stresses evaluation [8] and mechanical joint characterization [9], as well as, experiments results of FSW AA6082-T6 T-joints using different pin geometries [10] may be found in literature.

The Taguchi method is a quality technique widely used for optimization material processing technologies. This method is based on statistical analysis enabling the reduction of experiments. In order to determine optimum level for parameters and their influence in the process, data may be analyzed using an analysis of variance (ANOVA) or signal to noise (S/N) ratio. The method used in this work was the ANOVA analyze.

In the literature there is still a lack of studies concerning a proper determination of effective set of process parameters for FSW T-joints. Most of the studies that may be found are concerned with the prediction of properties and parameters optimization of FSW butt joints, e.g. [11-17].

In this work a step forward is made aiming at the industrial application of FSW. A study concerning parameters optimization of FSW AA6082-T6 T-joints using the Taguchi method and ANOVA analysis is presented.

METHODS AND MATERIAL

The welds were produced using three AA6082-T6 parts. Plates of 380x100x3 mm were used for the skins, and 380x31x3 mm plates for stringers (see Fig. 2). The welds were performed in the material rolling direction using a modified milling machine.

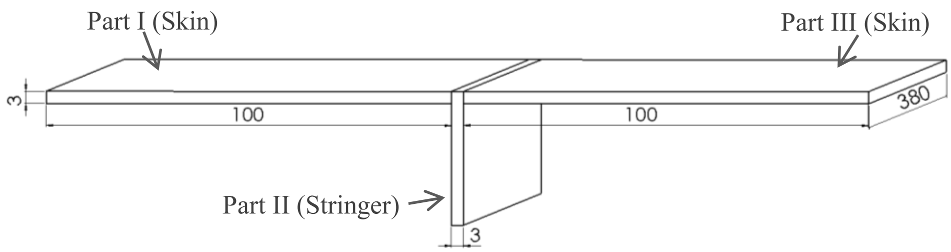


Fig. 2 - Welding T-joint configuration.

The parameters selected to optimized and their levels are presented in Table 1. The probe profile and diameter (probe/shoulder ratio was defined by variation of the shoulder diameter) were maintained constant. The probe used has a 6 mm diameter, and a conical shape with four flutes. The shoulder has a concave shape. The tool geometry is shown in Fig. 3.

Table 1 – Levels of the selected parameters

	Parameters	Unit	Level 1	Level 2	Level 3
A	Tool rotational speed	rpm	490	1000	1500
B	Welding speed	mm/min	76	216	360
C	Shoulder/Probe diameters ratio (D/d)	-	2 (12/6)	2.5 (15/6)	3 (18/6)
D	Probe distance from the root surface	mm	0.50	0.70	0.90

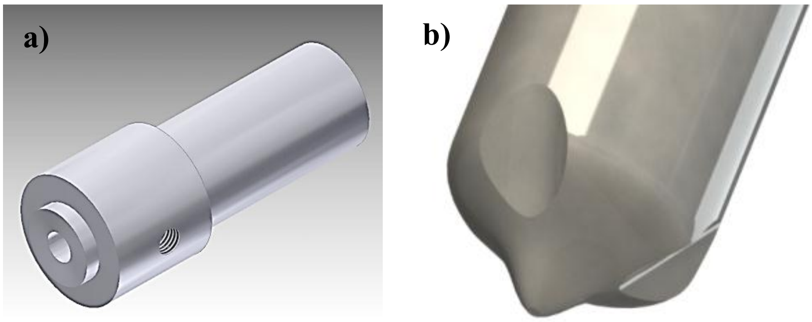


Fig. 3 - Pin and shoulder geometry: a) shoulder and tool body, b) pin detail.

To perform the experimental trials, the columns 1, 2, 5 and 9 were chosen from the Taguchi L27 orthogonal array (OA). Three levels for each parameter were selected to define the combinations of parameters to perform the FSW experiments (see Table 1). The OA for the experiments and the corresponding table with the parameters values is present in Table 2, where each line corresponds to a welding trial. Therefore, 27 different butt joints, were produced following the respective table.

After welding, mechanical tests were performed, including tensile and bending tests. Tensile test specimens drawn traversal to weld line were fabricated according to ASTM E8-M [18] in order to determine the tensile properties of weld and base material, using a 25 mm gage length and 1 mm/min cross-head speed. The load was applied at the skins perpendicular to the stiffener, where the skin tensile strength corresponds to the maximum load divided by its effective area.

The properties obtained were then used in an ANOVA analysis with a 95 % confidence level. Main effect plot were also performed.

In the ANOVA analysis it was not only studied each parameter effect in the properties, but also three interactions between parameters, as follows: tool rotational speed with welding speed (A*B), tool rotational speed with shoulder/probe diameters ratio (D/d) (A*C), and welding speed with shoulder/probe diameters ratio (B*C). With this analysis it was possible to determine the most influent parameters and their interactions in the tensile properties analysed.

The mean main effect plot makes it possible to determine the influence of each parameter in the joint tensile properties.

Table 2 – Taguchi orthogonal array used. In the left side are presented the columns of the L27 OA, and in the right side are presented the correspondent parameters values

Test	OA columns				Parameters			
	1	2	5	9	Rotational speed [rpm]	Welding speed [mm/min]	Shoulder/ probe diameter ratio (D/d)	Probe distance from the root surface [mm]
	A	B	C	D	A	B	C	D
1	1	1	1	1	490	76	2	-0.5
2	2	3	1	1	1000	360	2	-0.5
3	3	2	1	1	1500	216	2	-0.5
4	1	2	1	2	490	216	2	-0.7
5	2	1	1	2	1000	76	2	-0.7
6	3	3	1	2	1500	360	2	-0.7
7	1	3	1	3	490	360	2	-0.9
8	2	2	1	3	1000	216	2	-0.9
9	3	1	1	3	1500	76	2	-0.9
10	1	3	2	1	490	360	2.5	-0.5
11	2	2	2	1	1000	216	2.5	-0.5
12	3	1	2	1	1500	76	2.5	-0.5
13	1	1	2	2	490	76	2.5	-0.7
14	2	3	2	2	1000	360	2.5	-0.7
15	3	2	2	2	1500	216	2.5	-0.7
16	1	2	2	3	490	216	2.5	-0.9
17	2	1	2	3	1000	76	2.5	-0.9
18	3	3	2	3	1500	360	2.5	-0.9
19	1	2	3	1	490	216	3	-0.5
20	2	1	3	1	1000	76	3	-0.5
21	3	3	3	1	1500	360	3	-0.5
22	1	3	3	2	490	360	3	-0.7
23	2	2	3	2	1000	216	3	-0.7
24	3	1	3	2	1500	76	3	-0.7
25	1	1	3	3	490	76	3	-0.9
26	2	3	3	3	1000	360	3	-0.9
27	3	2	3	3	1500	216	3	-0.9

EXPERIMENTAL RESULTS

Tensile properties of the base metal are shown in Table 3. Test results from the 27 experiments resultant from the Taguchi method analysis are shown in Table 4.

Table 3 - Mechanical properties of AA6082-T6 aluminium alloy, base material [19]

Property	Value
Tensile strength [MPa]	323
Yield strength [MPa]	276
Elongation [%]	17.5

Table 4 – Average results obtained for each parameters combination

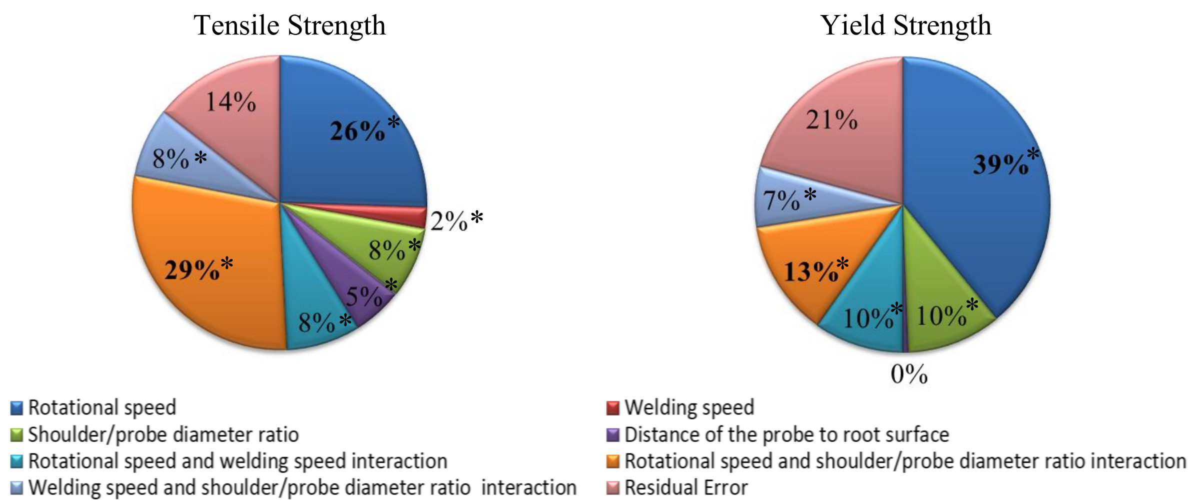
Test	Tensile properties	
	Tensile [MPa]	Yield$_{0.2\,\%}$ [MPa]
1	122	115
2	140	93
3	130	104
4	32	29
5	140	114
6	98	88
7	25	20
8	108	80
9	120	104
10	157	104
11	164	113
12	103	101
13	130	107
14	125	120
15	133	120
16	125	111
17	166	131
18	136	129
19	158	120
20	105	93
21	132	118
22	136	114
23	137	127
24	158	129
25	143	132
26	143	143
27	107	107

RESULTS DISCUSSION

Analysing the tensile test results, joint efficiencies (weld/base material strengths) of 56% and 51% for tensile and yield strengths respectively, were observed. Values of the same magnitude were found in [1].

An analysis of variance considering a level of confidence of 95%, was performed, in order to study which parameters have the highest influence in the tensile properties evaluated. The percentage of contribution obtained from this analysis is presented in Fig. 4. The analyses presents a satisfactory residual error, and almost all factors present an acceptable level of significance.

The tool rotational speed was proved to be the most influent parameter in tensile properties, while for the maximum load applied in bending tests it was the distance of the probe to the root surface that show an higher influence. Also, the interaction between the tool rotational speed and the shoulder diameter revealed that their effects are dependent on each other.



*parameter with significance level bellow to 0.05.

Fig. 4 - Parameters percentage contribution to the tensile properties.

Tensile strength seems to be greatly influenced by the tool rotational speed. However, it has verified a correct combination of the two speeds is of great importance in the joint tensile properties. When compared to tensile strength, a decrease of contribution of the two speeds interaction in the yield strength is verified. Also, the choice of the tool rotational speed is more important than the arrangement of the two speeds.

Main effects of each parameter and their interactions in the final joint tensile properties are presented in Fig. 5 and Fig. 6, respectably.

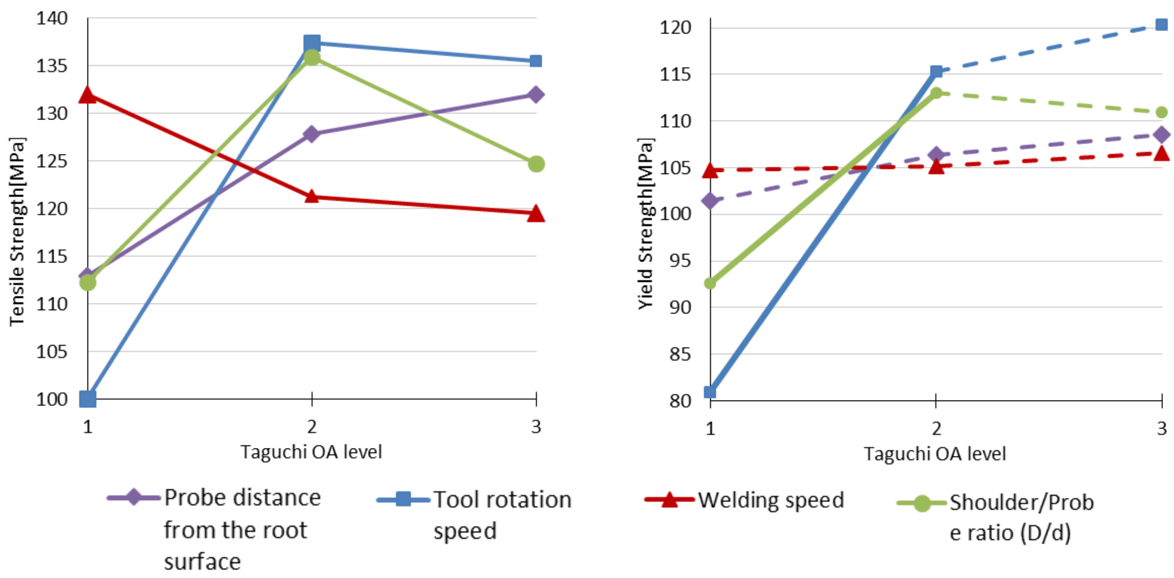


Fig. 5 – Main effect of the different parameters in the properties analysed. The solid lines denote the significant trends of each analysis using the Fisher method.

Concerning the rotational speed, which is the most influent parameter on tensile properties, in the different analyses it shows a trend to improve the joint mechanical properties if 1000 rpm are used, Fig. 5. This is verified in the analysis of tensile properties, presenting significant trends. A substantial improve of mechanical properties is verified with an increase of 490 to 1000 rpm, but changing from 1000 rpm to 1500 rpm, it is not so pronounced. Therefore, an optimum tool rotational speed was found. The inappropriate temperature and plastic deformation accomplished when slow tool rotational speed is used may explain the results. Also, high tool rotational speeds may lead to elevated temperatures enabling phase transformation and therefore a decrease of properties.

Concerning welding speed trends**,** it is shown that higher welding speeds leads to the lowest mechanical properties. Nonetheless, the welding speed appear not to have a significant influence on the yield strength. The decrease of tensile properties is more pronounced when the welding speed increases from 78 to 216 mm/min, than from 216 to 360 mm/min. When using higher welding speeds, the material has less time to achieve the proper temperature for plastic flow, leading to defect formation, as voids, resulting in a 'week' joint.

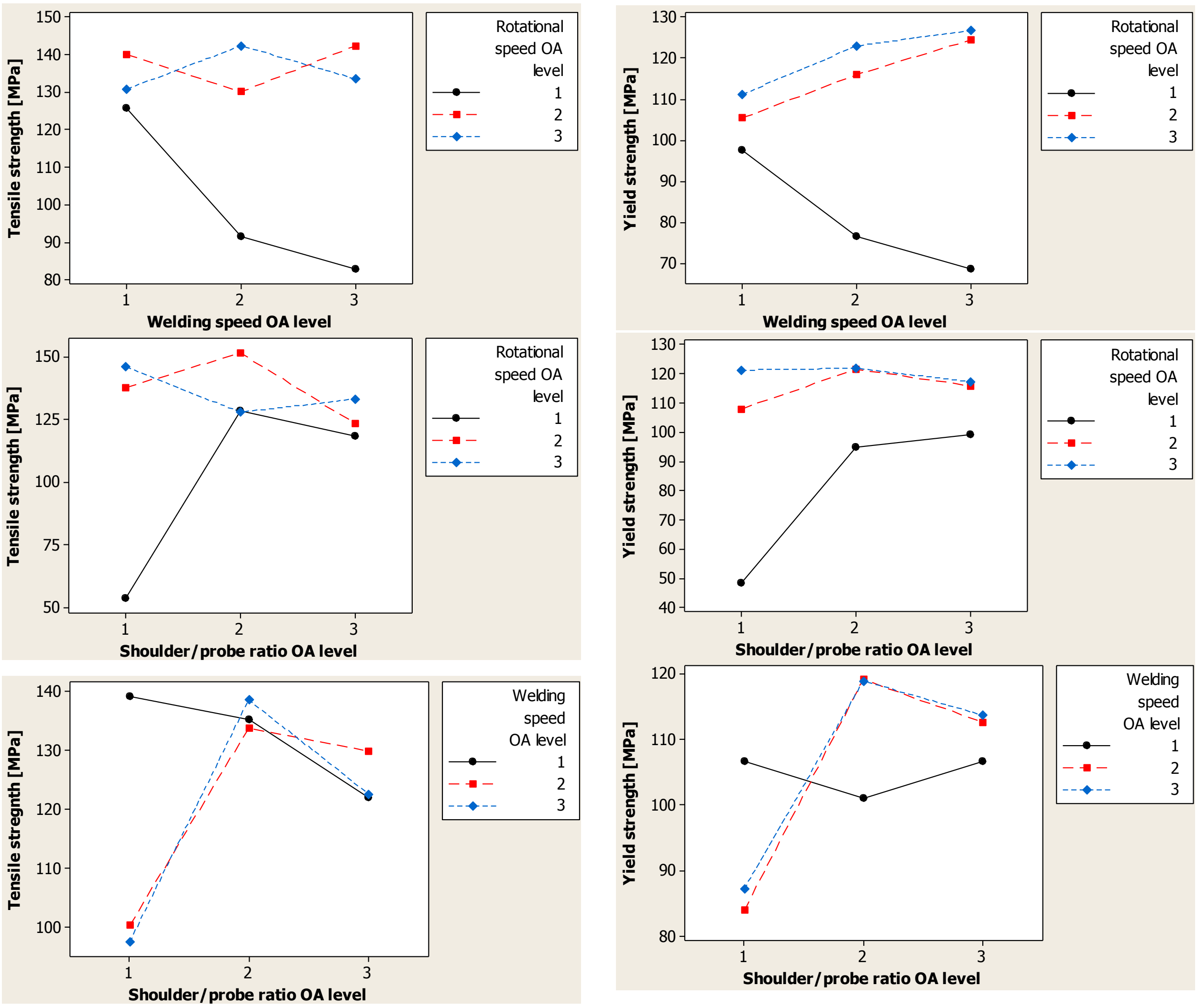


Fig. 6 – Main effect of the parameters interactions in the properties analysed.

Regarding the interaction between the rotational and welding speeds, presented in Fig. 6, it was demonstrated that the combination of higher tool rotational and welding speeds provides the best tensile properties. However, using the lowest rotational speed with the higher welding speed, the weakest mechanical properties are obtained. This reveals that the influence of the tool rotational speed in the several properties analysed is more pronounced when higher welding speeds are used. When working with lower welding speeds, it is almost assured that sufficient temperature and plastic flow will be achieved. However, when the welding speed is increased a shorter time is available for a good material stirring. Since less time is available for heating and inducing plastic flow, an increase of rotational speed is required.

On the subject of shoulder/probe diameters ratio it was observed optimum results for a shoulder of 15 mm diameter (for the 6 mm diameter pin used). A strong decrease in tensile properties analysed was verified in joints welded with the 12 mm and 18 mm diameter shoulders (see Fig. 5). It is well known that friction heat generated increases proportionally to the shoulder diameter, since most of the heat is generated at the interface of the tool shoulder and the work-pieces. Smaller shoulders may not provide enough heating, and thereby not enough plastic flow, resulting in degraded joint tensile properties. On the other hand, larger shoulders may lead to an excess of temperature, degrading tensile properties due to phase transformation.

In the case of the interactions between both speeds and the shoulder/probe diameter ratio, results demonstrate an existence of dependence between the parameters analysed (see Fig. 6). Worsts tensile properties are achieved with the use of lower tool rational speed and smaller shoulder and improving with the use of 1000 rpm and a 15 mm diameter shoulder. The combination of higher welding speeds and lower shoulder diameters achieved worsts properties, improving with the use of higher welding speeds and a 15 mm diameter shoulder. Considering these remarks, the best tensile properties may be achieve using a combination of 1000 rpm with a 15 mm shoulder diameter and 216 mm/min.

Concerning probe distance from the root surface, it was verified that the increase of the probe penetration provided the best tensile properties (see Fig. 5). The lowest penetration may lead to an ineffective joining, due to the lack of metal flow between the different parts, as reported in [6]. This increases the possibility of occurring kissing bond defects.

The analyses performed lead to a parameters combination of 1000 rpm with 216 mm/min, 0.90 mm from the probe to the root surface and a probe/shoulder diameters ratio of 2.5 (shoulder diameter of 15 mm), that resulted in the best joint ‘quality’.

CONCLUSION

It was demonstrated that Taguchi’s robust orthogonal array design method is suitable for the optimization of FSW T-joints.

The ANOVA approach leaded to the contribution of each parameter and their interaction in the properties analysed.

The joints presented an efficiency of 56% for the tensile and 51% for yield strengths regarding base material properties.

It was observed that the tool rotational speed was the most influent factor in joint tensile properties, and also that the welding speed and the probe/shoulder diameters ratio are strongly dependent on each other.

Improved joints may be achieved by using 1000 rpm with 216 mm/min, 0.90 mm from the probe to the root surface and a probe/shoulder diameters ratio of 2.5 (shoulder diameter of 15 mm).

It is important to mention that the optimization effort described here was only performed for AA6082-T6 aluminium alloy and using the presented tool geometry.

ACKNOWLEDGMENTS

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