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Experimental investigation of welding of aluminum alloys profiles and wrought plate by FSW

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1. Introduction

Friction Stir Welding (FSW) is a solid-state joining process which was invented by TWI in the UK in 1991 and is now being increasingly used in the welding of aluminum [1]. FSW has witnessed rapid development in many countries for manufacturing various structures from aluminum alloys. The process is commonly used in widening profiles by joining several extrusions in parallel or joining extrusions with plates in a butt joint. The method is applicable, e.g. for welding aluminum enclosure constructions (electrical appliances) for which it gives additional strength and durability [2-4]. The most remarkable benefits of FSW include time efficiency, high fatigue resistance for the joints and measuring accuracy when compared with conventional welding methods of welding aluminum alloys [5-9]. When welding long joints, FSW is especially cost-effective [10].

Although FSW has proven to be effective in welding aluminum, aluminum welding still represents a critical operation due to its complexity and the high level of defects that can be produced in the weld joint. The main problems are related to the properties of aluminum, which are high thermal conductivity, high chemical reactivity with oxygen and high hydrogen solubility at high temperatures [6].

Many groups [2-18] have been trying to optimize FSW processes and to characterize defects in Friction Stir (FS) welds over the past decade. On the other hand, the behavior of the oxide layer on the initial butt surface during FSW remains unclear, although oxide particles can adversely affect the weld appearance and mechanical properties of the weld.

A sound joint is strongly affected by several welding parameters. The tool tilt angle has an essential influence on the heat input into the material and the position of the defects in the weld [14]. The pin geometry has got a relevant influence both on the metal flow and on the heat generation due to the friction force [15]. Defects can also result on the welded joint when there is insufficient immersion of the tool shoulder into the metal being welded: a large gap in the butt joint and shifting of the butt axis relative to the tool; insufficient force of pressing the tool on the surfaces of the part being welded during welding; a low rate of tool rotation, substantial welding speed; unreliable fixation of the edges being welded and using a tool with a small diameter of the lip [11 - 13].

The objective of this experimental investigation was to find out the different possibilities to reduce some of the defects when welding extruded profiles (EN AW-6005 or EN AW-6063) in a joint with plate (EN AW-5754) by varying the welding process parameters with and without aluminum oxide using mechanized FSW. The experiment established the ranges in the differences of parameters used in the experimental investigation which produced welded joints that are free from defects.

The influence of process parameters on defect formation in welds was evaluated in welding a butt joint on the profiles and plates. The technological factors (angle of the tool to the vertical, fixtures, penetration depth of the tool, etc.) were kept at an appropriate level throughout the investigation. The weld defectiveness was determined by visual inspection, macropictures of the weld appearance, as well as using macrosection investigations. The mechanical tests were carried out on the welded parts that were both cleaned (oxide removal) and not cleaned which yielded definite results.

The chemical composition of the Al alloys is given in Table 1, and the material thicknesses used in the investigation were 3 mm.

Table 1

Chemical composition of aluminum alloys in weight percentage

Alloys	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other (total)	Al
EN AW-6005 (wt %)	0.6-0.9	0.35	0.1	0.1	0.4-0.6	0.1	0.1	0.1	0.15	Balance
EN AW-6063 (wt %)	0.2-0.6	0.35	0.1	0.1	0.45-0.9	0.1	0.1	0.1	0.15	Balance
EN AW-5754 (wt %)	0.4	0.4	0.1	0.5	2.6-3.6	0.3	0.2	0.15	0.15	Balance

2. Experimental procedure

The equipment used to carry out this experimental investigation was Esab FSW 5UT LEGIO^{TM} conventional load type FSW machine with a tool that has a columnar shape with a screw probe. The two halves to be joined were rigidly fixed before the welding operation. The process is illustrated in Fig. 1, where an especially designed rotating pin, which is an integrated part of the tool, plunges into the adjoining edges and locally plasticizes the joint line during its move. The welding was carried out by a 'backward inclined tool' at a tool inclination angle of 2.5°

during the study. The diameter and the length of the probe were 6 mm and 2.7 mm, respectively. The diameter of the shoulder was kept at 20 mm. All the above dimensions were kept constant during the study.

Before welding, aluminum oxide layers were removed from half of the samples of the pieces to be welded from both surfaces of the aluminum alloys by scratch brushing. In the experimental investigation, the following process parameters were changed: downward push force F, which is the force of pressing the working tool on the surface of the parts being welded, welding speed V_w, and rotation speed and direction V_{rot}.

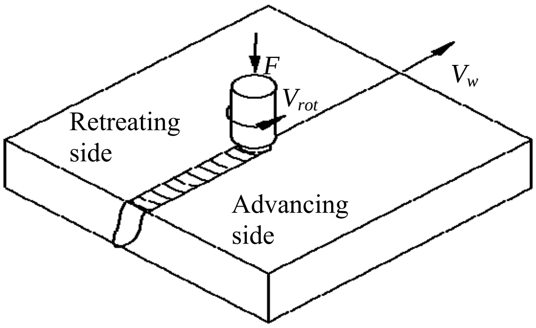


Fig. 1 Block diagram of FSW process with counterclockwise direction of the tool

The friction stir welds were performed using the same parameters for the two extruded profiles and the plates. The tool downward push force was changed from 9 to 14 kN. The tool rotation speed and the welding speed were changed from 1000 to 1600 rpm and from 700 to 1300 mm/min, respectively. The directions of the tool were changed to clockwise and counter clockwise.

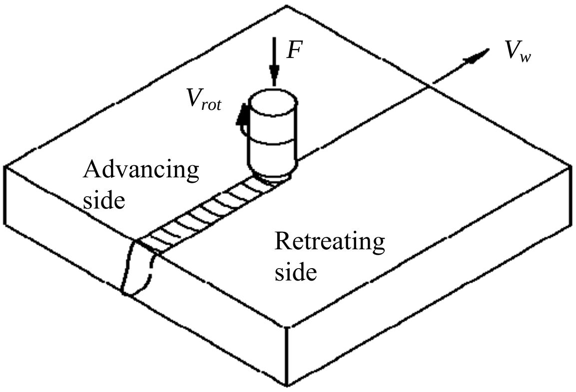


Fig. 2 Block diagram of FSW process with clockwise direction of the tool

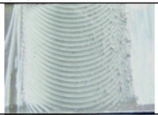
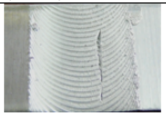
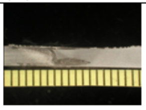
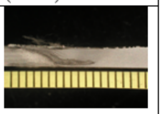
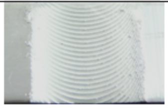
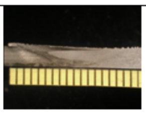
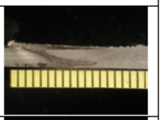
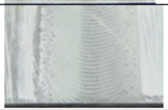
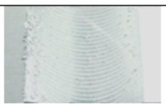
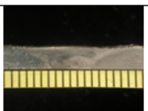
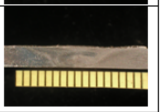
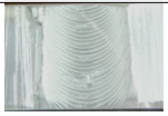
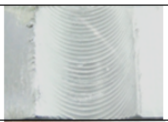
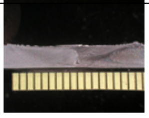
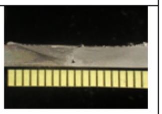
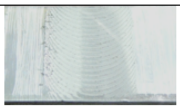
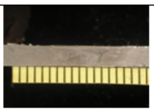
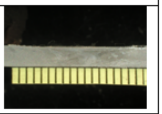
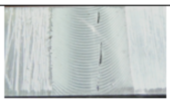
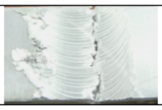
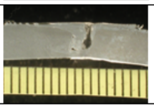
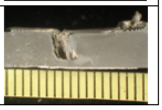
3. Results and discussion

In the study, the weld quality was based on the appearance of the weld bead and the macrosection of the weld. With a view to achieve an aesthetic weld, the process parameters were changed many times and the best parameters were chosen**.** Table 2 shows the typical appearances and macrosections of the extruded profiles and the plates. *C* denotes the workpiece was clean (oxide removed) and *No C* denotes the workpiece was not clean. Metallurgical inspection was performed on the cross-sections of the FSW joints. They were polished and etched for 1 min with 100 ml of H_2O, 10 ml of hydrofluoride (HF) and 15 ml hydrogen chloride (HCl) for optical microscopic observations.

A series of samples were welded under various processing conditions with the profile 6005 on the advancing side and the plate 5754 on the retreating side as in Fig. 1. When the welding speed was 900 mm/min, rotational speed 1200 rpm and downward push force 14 kN, the quality of the weld was much superior to the weld performed with a low welding speed of 700 mm/min. When

Table 2

Typical appearances and macro-sections of some of the welds of 3 mm thickness plates

Reports	Weld appearance (*C*)	Weld appearance (*No C*)	Macro-sections (*C*)	Macro-sections (*no C*)
A				
B				
C				
D				
E				
F				

the speed exceeded 900 mm/sec, there were cracks at the portion of the plate which was not cleaned as compared with the portion that was cleaned (Report A) as appears in Table 2. The ratio of the welding speed and frequency of tool rotation also essentially influences the degree of heating and level of metal plasticizing. Therefore, lowering the welding speed or increasing the frequency of tool rotation may lead to metal overheating and thus impair the quality of the weld surface. [11]

When the rotational speed was changed to 1000 rpm, and the downward push force and the travel speed were kept at 14 kN and 900 mm/min, respectively, the quality of the weld was better as can be seen in Report B in Table 2.

The rotational speed and the welding speed mainly affect the heat evolution in the welding zone. If the ratio of rotation speed and displacement speed along the butt is not enough, the heat released may not be enough for plasticizing the volume of the metal necessary for filling the empty space produced by the tool probe [11].

When the rotational speed was changed to 1400 rpm, and the downward push force and the travel speed were kept constant as in Report B, it was noticed that there was splashing of the pool at the side. As the rotational speed was further increased to 1600 rpm, the quality of the weld was not good especially at the section that was not cleaned.

On the other hand, changing the downward push force to 12 kN and keeping the rotational speed and the traveling speed at 1200 rpm and 900 mm/min, respectively, the weld quality appearance was much similar like the one in Report B. Changing the tool downward push force to 16 kN and maintaining the other variables, it was noticed that the weld quality was not as good as Report B parameters. Therefore at a given tool downward push force, excellent joints are obtained at suitable tool rotational speeds and welding speeds. At the highest tool downward push force of 14 kN, the range of the optimum FSW situation was wider than the others. It was then noticed that the border for the higher rotation speed and higher welding speed range is not considerably affected by the tool down push force. It was established that the optimum parameters for welding of profile 6005 and plate 5754 are obtained with 12 kN downward push force, 1200 rpm rotational speed and 900 mm/min traveling speed with the profile on the advancing side and the plate on the retreating side.

In contrast, maintaining the best process parameters as in Report B with profile 6005 and plate 5754 shown in Fig. 2 with the plate on the advancing side and the profile on the retreating side, it was noticed that the quality of the weld was not good.

A series of investigations were carried out with repeatedly changing the process parameters with the second extruded profile 6063 and the plate 5754 with profile 6063 on the advancing side and the 5754 plate on the retreating side as in Fig. 1. The weld joints produced were not of good quality especially on the portion of the joints that were not clean.

Changing the direction of rotation of the tool, that is the plate on the advancing side and the profile on the retreating side as in Fig. 2, the qualities of the welds were much better than the qualities produced shown in Fig. 1 with the same profile 6063 and plate 5754. It was then accomplished that the good quality of the weld may come as a result of the rotational direction of the tool. The best weld quality of this series resulted from 13 kN downward push force, 1200 rpm rotational speed, and 900 mm/min travel speed as in Report C in Table 2.

It was then concluded that the failure of the quality of the welds with the 5754 plate on the retreating side and the profile 6063 on the advancing side as in Fig. 1, was due to the direction of the tool which is brought about by irregular stirring of the weld pool. It is considered that the irregular stirring is caused by the different temperatures between the base metals. Repeating the same process parameter as in Report C and changing the direction of rotation as in Fig. 1, the quality of the weld appearance was good but that of the macrosection shows that there was lack of fusion as can be seen in Report D in Table 2. The parameters of Report E (13 kN, 1400 rpm, 1300 mm/min) yielded good results especially on the portion of the workpiece that was clean.

Report F in Table 2 shows the poor weld quality of weld appearance and macrosection of weld that was clean and no clean of parameters; 14 kN downward push force, 1400 rpm rotational speed and 1300 mm/min travel speed. The tool rotation was counter clockwise direction, and the profile 6065 on the advancing side and plate 5754 on the retreating side.

Defects are formed outside the optimum FSW conditions. However, when there is excessive heat input, there are huge accumulations of flash of the pool. In other words, when the heat input is low, there are cracks on the weld or insufficiencies in the joint. This comes as a result of lower rotation speeds and higher welding speeds. To produce an ideal defect-free weld, the revolutions per minute of the cylinder shoulder-pin assembly, travel speed, downward push force and pin tool design have to be optimized [3].

4. Mechanical tests

From each welded plate, two bend test and four tensile test specimens were cut out using the sawing machine. Tensile test specimens were machined using milling in to the standard dimensions. The mechanical tests were carried out to determine whether the aluminum oxide influences the weld properties and to find differences that the process parameters cause to the mechanical performance of the joints [19, 20].

4.1. Bending tests

The machine used in the testing was a universal electro-mechanical tensile and bend testing machine WPM20. The bend tests were carried out from the transverse face and root sides. The welded joints were visually examined and machined into standard test specimen dimensions (ISO 5173) [21]. The diameter of the former was 30 mm and distance between support rollers 38 mm. Most of the welds showed a 180° bending angle which indicated good quality. From the bend test results in Figs. 3 to 5 it can be seen that the results were slightly better for the profiles that were cleaned compared to the profiles that were not cleaned. This can be seen from Table 2 particularly when welding parameters are near their upper limits. When the rotation speed exceeds 1400 rpm, travel speed

900 mm/min and tool push downward force 12 kN, the bending angle starts to decrease in welds with no oxide layer removal. The same effect cannot be seen in the cleaned welds. On the other hand, it is not necessary to remove the oxide layer from surfaces prior to welding, if welding parameters are near their safe mean values.

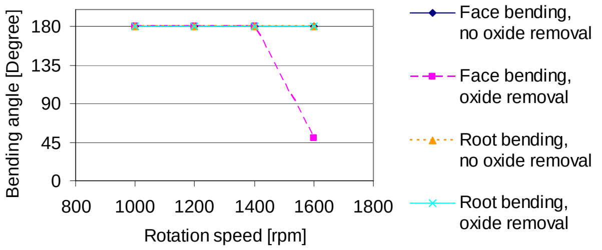


Fig. 3 Bending angle as a function of rotation speed. Travel speed 900 mm/min and tool plunge downforce 14 kN. Profile material EN AW-6005

As far as the effect of the tool rotating speed is regarded, overall it can be assessed that it is not a critical welding parameter. The welds have good bending properties with all rotating speeds. The only exception came up with 1600 rpm, when the specimen (with oxide removal) fractured already in an angle of 50 degrees.

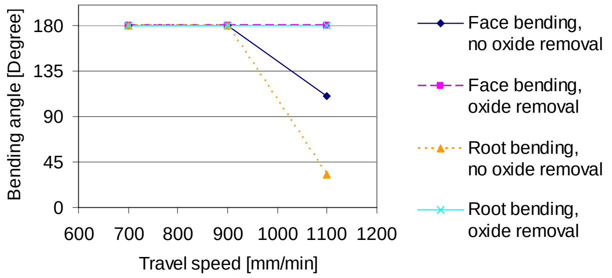


Fig. 4 Bending angle as a function of travel speed. Rotation speed 1200 rpm and tool plunge downforce 14 kN. Profile material EN AW-6005

Travel speed seems to be the most critical parameter in FSW welding. When exceeding the speed of 900mm/min, the bending properties start to decrease. This happened especially, when the oxide layer was not removed.

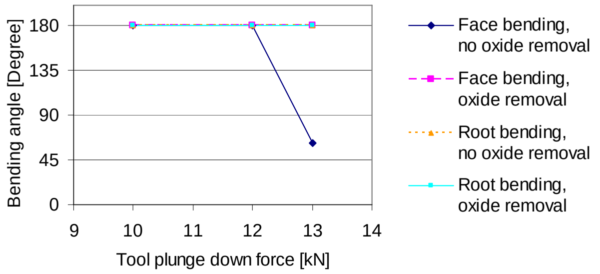


Fig. 5 Bending angle as a function of tool plunge downforce. Travel speed 900 mm/min and rotation speed 1200 rpm. Profile material EN AW-6063

Tool plunge downforce is of same importance as the travel speed, when evaluating critical welding parameters in FSW. The force can vary greatly without any influence on the bendability of the welded joint. Again, oxide removal seems to slightly improve fracture resistance under bending.

4.2. Tensile tests

Transverse tensile tests were carried out according to standards EN 895 and EN 10002-1. The results of tensile strengths are presented in Figs. 6 to 8 and results of percentage elongations in Figs. 9 to 11. Materials welded by FSW have typically the following mechanical properties:

EN AW-6005T6: R_m=260 N/mm^2, A_5=8 %
EN AW-6063T6, R_m=205 N/mm^2, A_5=8 %
EN AW-5754 O/H111, R_m=190 N/mm^2, A_5=17 %

In the tests, all tensile specimens fractured from the weld. Tensile strengths were at the level of 200-210 N/mm^2 with EN AW-6005/EN AW-5754 and 170-180 N/mm^2 with EN AW-6063/EN AW-5754. The influence of the oxide layer was of minor importance in tensile tests compared to bend tests. The impact is of most significance when trying to increase the travel speed (Report A). The tensile strength achieved was constant in the welds with cleaned surfaces, but without oxide removal, the tensile strength dropped drastically when exceeding a travel speed of 800 mm/min. A similar influence can be detected, but not so clearly, when changing the tool push downward force. After 12 kN the tensile strength starts to decrease in case of EN AW-6063.

Percentage elongation is defined as the maximum permanent elongation of the material after fracture. Percentage elongations measured in tensile tests were 8–10% with EN AW-6005/EN AW5754 and 1–10% with EN AW 6063/EN AW5754. The most critical process parameter in

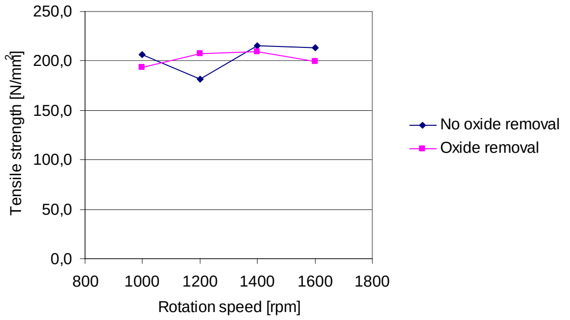


Fig. 6 Tensile strength as a function of travel speed. Rotation speed 1200 rpm and tool plunge downforce 14 kN. Profile material EN AW-6005

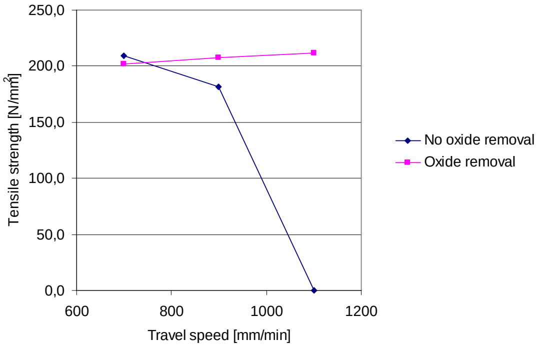


Fig. 7 Tensile strength as a function of tool plunge down force. Travel speed 900 mm/min and rotation speed 1200 rpm. Profile material EN AW-6063

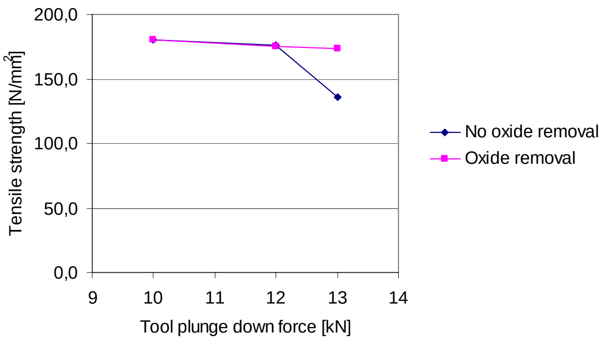


Fig. 8 Tensile strength as a function of tool plunge downforce. Travel speed 900 mm/min and rotation speed 1200 rpm. Profile material EN AW-6063

terms of elongation proved to be the welding travel speed. When exceeding the speed of 900 mm/min, elongation decreases rapidly (Fig. 10). Rotation speed seems however to be of minor importance. Oxide removal gives better elongation values only, if the welding speed and tool plunge downforce are near their upper limits (Figs. 10 and 11).

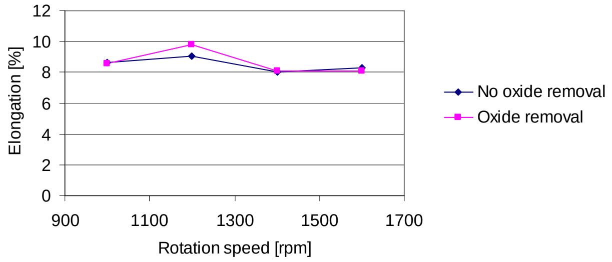


Fig. 9 Elongation as a function of rotation speed. Welding speed 900 mm/min and tool plunge downforce 14 kN. Profile material EN AW-6005

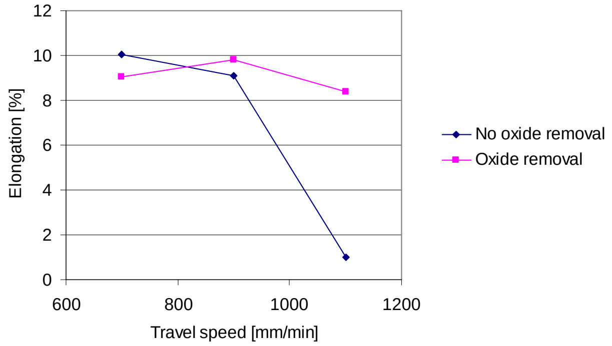


Fig. 10 Elongation as a function of travel speed. Rotation speed 1200 rpm and tool plunge downforce 14 kN. Profile material EN AW-6005

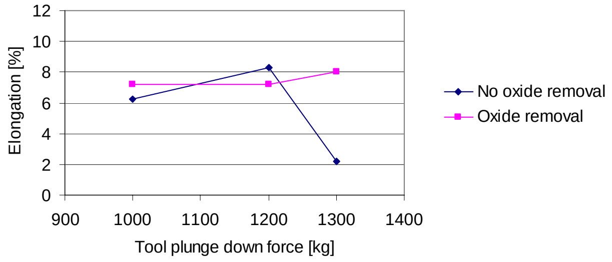


Fig. 11 Elongation as a function of tool plunge downforce. Travel speed 900 mm/min and rotation speed 1200 rpm. Profile material EN AW-6063

The aluminum oxide particles are distributed at the fracture texture of the tensile sample, as shown in Fig. 7. These aluminum oxide particles could be the factor why the ductility of the joint decreases dramatically. Ductility is influenced by the chemistry of the alloys, and thermal strain is influenced by the welding process, heat input, joint configuration and fixturing, among others.

Considering the FSW process, the oxide layer on the initial butt surface experiences intensive stirring; it would be smashed to oxide particles, so that the oxide particle distribution in the weld may be an initiation site for tension fracture. Therefore, the present study also examines the fractography of the tensile sample.

Observation is made regarding the two configurations 1 and 2 of the joints. It should be observed that for every analyzed case study the joints obtained in configuration 1 always showed mechanical performances definitively greater than the ones welded in configuration 2. In particular, for the joint welded in configuration 1, resistance capacity in the shear test was obtained with respect to the one in configuration 2.

5. Conclusions

Thus, as a result of performing a set of scientific experimental investigations, as well as on the basis of the data from foreign publications, the ranges of variation in the main parameters of the process were established, which allow producing sound joints of sheet aluminum alloys by FSW.

It was noticed in the experimental study that the rotation direction has a lot to do with welding extruded profiles and plates or different Al alloys by the FSW method. Defects can result from choosing the wrong rotational direction of the tool; namely, which material takes the rotation first.

The mechanical tests show the results of the welded joints when cleaning and no cleaning were done with different parameters. Welded joints with profile EN AW-6005 and EN AW-5754 have good bending properties compared to profile EN AW-6063 and EN AW-5754 due to the differences of mechanical properties. It can be said that cleaning does not have a great influence on tensile strengths; but if more productivity is needed, then oxide removal is recommended.

Experimental results showed that the quality of weld formation in FSW of aluminum alloys 3 mm thick mainly depends on such process parameters as size and configuration of the tool lip and pin working surfaces, force of tool lip and pin working surfaces, force of tool clamping on sheet surfaces and depth of its immersion into the metal being welded, tool rotation frequency and welding speed. The results of the parameters for the clean and not clean areas in terms of the weld qualities have thus been established.

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TRINTIMI SUVIRINTO ALIUMINIO LYDINIO PROFILIŲ IR KALTINIŲ PLOKŠČIŲ EKSPERIMENTINIAI TYRIMAI

Reziumė

Straipsnyje aprašomas bandymas, kuriuo siekiama sumažinti keletą defektų ir gauti geros kokybės siūles mechanizuotai trintimi suvirinant Al-Mg-Si lydinio profilius EN AW-6005 ir EN AW-6063 bei Al-Mg lydinio kaltinę plokštę EN AW-5754 sandūrine 3 mm pločio siūle. Suvirinama medžiaga vienu atveju buvo iš dalies nuvalyta (pašalintas aliuminio oksidas), kitu – nenuvalyta. Defektų profilių suvirinimo metu atsiranda dėl skverbties stokos medžiagoje, netikslaus proceso parametrų nustatymo, netinkamos įrankio sukimosi krypties. Tačiau daugumos defektų priežastys suvirinant trintimi lieka nežinomos.

Pagrindiniai suvirinimo proceso parametrai bei šių aliuminio lydinių suvirinimo siūlės mechaninės savybės buvo analizuojamos aliuminio oksidą pašalinus ir jo nepašalinus. Atlikti mikropjūviai ir mechaninių savybių tyrimai parodė, kad įrankio sukimosi kryptis turi įtakos suvirinimo kokybei dėl neįprastos suvirinimo srities susidarymo aplink skirtingo kietumo suvirinimo siūlę. Aliuminio oksido dalelės neturi didelės įtakos tempimo stiprumo ribai, tačiau norint padidinti našumą, oksidus rekomenduojama pašalinti.

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EXPERIMENTAL INVESTIGATION OF WELDING OF ALUMINIUM ALLOYS PROFILES AND WROUGHT PLATE BY FSW

Summary

This paper describes an attempt to reduce some of the defects and to produce good quality welds when welding Al-Mg-Si alloy profiles EN AW-6005 or EN AW-6063 and Al-Mg alloy wrought plate EN AW-5754 in butt joints of thickness of 3 mm by using mechanized Friction Stir Welding (FSW). The weld joints were performed on materials partly cleaned (aluminum oxide elimination) and not cleaned. The defects when welding these profiles and a plate can come as a result of lack of penetration, incorrect

setting of the process parameters, and wrong rotational direction of the tool. However, the sources of the defects in FSW remain uncertain.

The effect of the main welding process parameters and the mechanical properties of these aluminum alloy welds were studied in the oxide and not oxide portions. From the macro-sections and the mechanical properties tests, it was drawn that the rotational direction can change quality of the weld. This is due to the unusual stirring of the weld pool which brings about differences in the hardness of the weld joints. The aluminum oxide particles do not have a great influence on tensile strengths, but if more productivity is needed, then oxide removal is recommended.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ СВАРЕННЫХ ТРЕНИЕМ ПРОФИЛЕЙ И КОВАНЫХ ПЛАНОК ИЗГОТОВЛЕННЫХ ИЗ АЛЮМИНИЕВЫХ СПЛАВОВ

Резюме

В статье описана попытка уменьшить некоторые дефекты, возникающие при выполнении механизированной сварки трением профилей типа EN AN-6005 и EN AN-6063, изготовленных из сплава Al-Mg-Si и кованой планки EN AN-5754, изготовленной из сплава Al-Mg. Тип сварки стыковой, его толщина 3 мм. Сварка произведена при частичной очистке материала (удаляется оксид алюминия) и без нее. Дефекты, возникающие при сварке профилей, появляются из-за недостаточного проникновения в материалах, неточной установки параметров сварочного процесса, неправильного направления вращения инструмента. Однако исток множества дефектов при сварке трением остается неизвестным.

Основные параметры сварочного процесса и механические свойства сварочного шва упомянутых алюминиевых сплавов исследовались при удаленном алюминиевым оксиде и без его удаления. Выполненные исследования микрошлифов и механических свойств показали, что на качество сварочного шва оказывает влияние направление вращения инструмента. Это происходит из-за формирования необыкновенной сварочной зоны вокруг сварочного шва разной твердости. Частицы алюминиево оксида не оказывают большого влияния на предел прочности при растяжении, однако при желании увеличить продуктивность процесса, удаление оксидов желательно.

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