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Key words: friction stir welding, plunge stage, triangle pin, temperature distribution

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EXPERIMENTAL STUDY OF THE TEMPERATURE DISTRIBUTION AND MICROSTRUCTURE OF PLUNGE STAGE IN FRICTION STIR WELDING PROCESS BY THE TOOL WITH TRIANGLE PIN

Considering the developing role of the friction stir welding in manufacturing industry, a complete study on the process is necessary. Studies on each stage of the process in particular, provide a better understanding of friction stir welding, and specially friction stir spot welding. In this study, plunge stage has been studied by experimental methods for investigating the temperature distribution around the tool during the plunge stage and microstructure changes of the workpiece. Experiments were performed on aluminium 7050 plates with coincident measurement of temperature. In the study, the tool which has a triangle pin is used. The results of this study are used as initial conditions for theoretical analysis of welding process. The results show that the temperature distribution around the tool is quite asymmetric. The asymmetric distribution of temperature is due to nonuniform load distribution underneath the tool and tilt angle of it. The temperatures of the points behind the tool are higher compared with points located forward the tool. Microstructural studies showed that four regions with different microstructures are formed around the tool during the process. These areas were separated based on differences in grain size and elongations. Grains near the tool are elongated in a particular direction that show the material flow direction.

1. Introduction

Friction stir welding (FSW) was invented by the Welding Research Institute (TWI) in 1991 [1]. Despite of the novelty, FSW became popular in manufacturing, particularly in aerospace, marine and automotive industries.

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FSW is a solid state joining process that is performed at temperatures below the solidus temperature of the workpieces and there is no melting during the welding. Therefore, it is a perfect method for welding of low fusion weldable materials, especially non-ferrous metals such as high strength aluminium alloys (like 2xxx and 7xxx series), copper and magnesium. Recently, joining of high melting temperature metals such as steels is done by the FSW method by Lienert et al. [2].

This process is performed in three steps called the plunge stage, the welding stage and finally ejecting the tool. At the first step, a non-consumable tool with rotational motion penetrates into the workpiece at the interface on the weld line by applying vertical force (plunge force). Penetrating of the tool into the workpiece continues until the full penetration of the pin and the shoulder contacts with the workpiece. Due to the friction between the tool and the workpiece, heat is produced and the temperature is raised. Penetration of the tool causes plastic deformation in the workpiece that leads to a further heat production as well as friction. In Figure 1, a schematic diagram of the beginning of the FSW process, the plunge stage, with process parameters are shown.

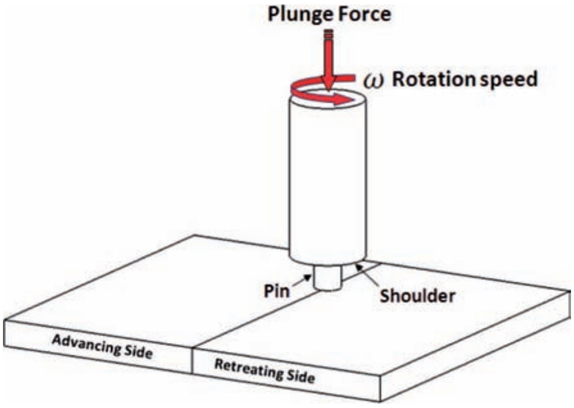

Fig. 1. Parameters in FSW process

The plunge stage determines the initial thermodynamic conditions of the workpiece, therefore it is so critical for investigation of the process. The dynamic nature of this stage makes it very difficult to be investigated. Complete study of plunge of the tool is important for further understanding of the process and improving the tool design, especially for welding high strength alloys (as the tool wear occurs at this stage). There are a few researches focusing on the plunging, and thus more studies (experimental, numerical and theoretical analysis) is necessary to understand changes during this stage.

Finite element based numerical analysis models, proposed to simulate plunge stage. Schmidt et al. [3, 4, 5] suggested a numerical model using

ABAQUS/Explicit and the Lagrangian-Eulerian (ALE) technique. They simplified the process by assuming the contact between the tool shoulder and the surface of the workpiece from the beginning of the process in the model. They ignore the gradual penetration of the tool in the workpiece. Goetz and Jata [6] developed a two-dimensional model for simulating the material flow around the tool and the penetration of the tool by using the commercial finite element code, DEFORM 3D. Gerlich et al. [7] developed a three-dimensional model for analyzing friction stir spot welding, in order to investigate the plunge stage. They used Computational Fluid Dynamic (CFD) method to study the process. Kakarla et al. [8] propounded a model to simulate tool penetration, using solid mechanics theory. They studied the process just for 0.3175 mm depth. Guerdoux et al. [9, 10] used two commercial codes, THERCAST and FORGE3 to simulate the FSW process. In their model material behavior was assumed in accordance with Norton-Hoff law. Santella [11] in an experimental investigation studied the penetration of the tool in a metal matrix composite of aluminium (Al 6061 + 20wt%Al2O3). He measured the amount of force and torque imposed to the tool during the process.

Studies have been limited to simple tools (tools with a cylindrical pin) and tools with a pin like squares, triangles, etc. have not been studied. These tools have found many applications today, so it is worthwhile to study. In this paper, the first stage of the friction stir welding process, the plunge stage, is studied by using experimental methods. In this study, the tool with triangle pin is used. Temperature distribution in the workpiece during tool plunge has been discussed. The results of this study can be used as initial conditions for the analysis of the welding process. The plunge stage determines the initial thermodynamic conditions of the workpiece, therefore it is so critical for investigation of the process. The dynamic nature of this stage makes it very difficult to be investigated. Complete study of plunge of the tool is important for further understanding of the process and improving the tool design, especially for welding high strength alloys (as the tool wear occurs at this stage). There are a few researches focusing on the plunging, and thus more studies (experimental, numerical and theoretical analysis) is necessary to understand changes during this stage.

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2. Experimental procedures

According to the purposes of this study, 7075 aluminum alloy has been selected for plunging tests. This alloy is widely used in aerospace and marine applications. The chemical and mechanical properties of 7075 aluminum alloy are given in Table 1. To allow for accurate measurement of temperature, especially in underneath the shoulder, the sheets with a thickness of 10 mm was used with dimensions 100 mm × 70 mm. Sheet surfaces have been sanded to remove contaminants and oxides.

Table 1.

Chemical and mechanical properties of alloy 7075

Cr	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zn**	**Hardness (Brinell)**	**Ultimate Tensile Strength (MPa)**	**Tensile Yield Strength (MPa)**	**Elongation at Break (%)**
0.2	1.5	0.3	2.4	0.15	0.14	0.1	5.4	150	572	503	11

Measuring the temperature in different points of the workpiece is performed by plugging K-types thermocouples at pre-specified locations. Thermocouples are connected to a Data-Logger that can simultaneously record temperature of 8 points every tenths of a second and during the process measured temperature are recorded. All the temperature measurement instruments were calibrated before the tests and able to measure temperatures up to one-tenth degree of Celsius. Temperatures of 4-point of the workpiece during processing have been measured. Location of the points is shown in Fig. 2. The points are intended symmetrically on either side of the tool to reveal the different temperature in the advancing, retreating, back and front of the tool underneath the shoulder during the process. Simultaneously, temperature of four points on the surface of the plate is recorded by another thermocouple. A vertical mill that could have automatic vertical and horizontal movement was used in the process. The test was conducted at the tool rotation speed of 1100 rpm and plunge speed was 0.1 mm s^{-1}.

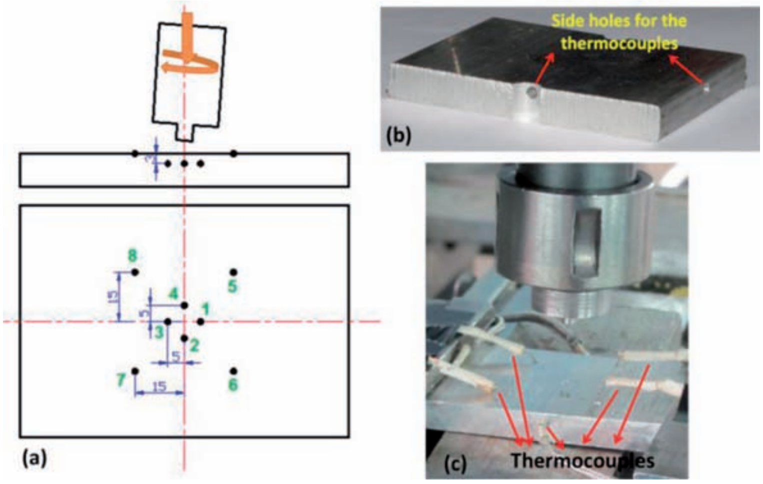

Fig. 2. (a): the location of the thermocouples during the welding process, (b): workpiece with side holes for thermocouples, (c): thermocouples in the experimental procedure

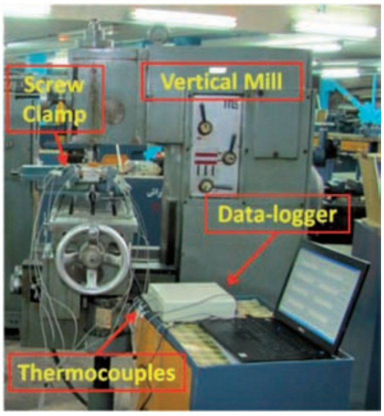

Fig. 3. Welding equipment and temperature measurement instruments

The tool was made of H13 hot work tool steel. After cutting from 20 mm diameter rod and shaping by the machining, the tool was heat treated to increase the hardness to about 52 Rockwell. Figure 4 shows the used tool.

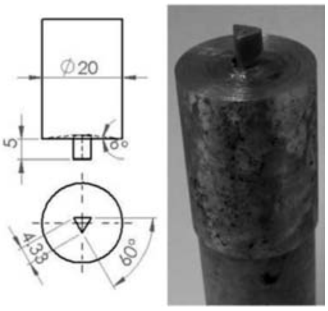

Fig. 4. The tool with triangle pin (all dimensions are in millimeters)

To control and prevent the movement and torsion of workpiece during the process, simply screw clamp was used and also a plate made of H13 was used as a backplate to prevent deformation of the workpiece during the process.

3. Results and discussion

Temperature-time graph that recorded by thermocouples attached to the workpiece during the process is shown in Fig. 5. The downward section of the curve is for unplugging of the tool and the maximum temperature represents the end of the plunge stage. It can be seen that the temperature distribution is asymmetric around the tool. Due to the tool's tilt angle, distribution of load underneath the tool is not uniform, therefore the friction force and frictional work is different at each point under the tool. Thus, heat produced at any point is different, which causes that distribution of temperature is asymmetric around tool. Point 1, 2, 4 and 3 have the highest temperature during process, respectively.

At the beginning of the plunge and before shoulder contact with the workpiece surface, workpiece temperature rises slowly, and the temperature difference between the temperature of the points is neither great nor significant. However, immediately after the first contact of the shoulder, the temperature rises rapidly. Temperature graph of points 1 and 2 are close together at the beginning of the plunge, but on reaching the end of the process, temperature difference between them is significant and equal to 6% at the maximum amount. Temperature of point 3 is always significantly less than of other points and for the maximum value has 4% with Point 2, 10% with Point 1 and 2% with point 4 temperature difference. Table 2 shows the

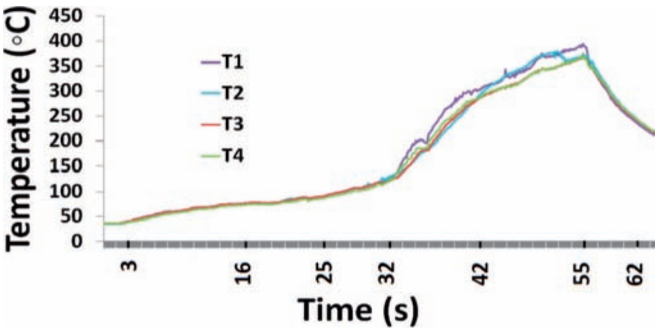

Fig. 5. Temperature changes during the plunge for each thermocouple for each thermocouple below the surface

Table 2.
Maximum temperature measured and calculated at the end of the plunge in the points 5-8

Thermocouple position	**Maximum temperature (°C) Measured**
Point 1	395
Point 2	370
Point 3	357
Point 4	364

maximum measured temperature at the end of plunging of the tool for each thermocouple.

The temperature of four points on the surface of the workpiece, which are located further away from the tool, is shown in Fig. 6. There is a large difference between the temperatures of the points. The temperature difference between these points and those are located under the surface is significant. Generally, the temperature is higher behind the tool. At the beginning of the process, points had a small temperature difference, and once with shoulder contact, the temperatures were diverged. The rate of the temperature difference between the points on the surface is higher than those are in depth. The maximum temperature of the points is shown in Table 3.

The maximum temperature difference between the points on the surface is significant so that the difference between the temperature of points 5 and 6 is less than 1%, point 6 and point 7 is 5% and point 8 point 6 is almost 10%. At the end of the plunge stage, the points under the surface and near the tool are becoming isothermal with high rate, while points at the surface and far from the tool are slowly becoming isothermal. It is expected that, if the heat transfer coefficient is higher, the rate of becoming isothermal will be faster.

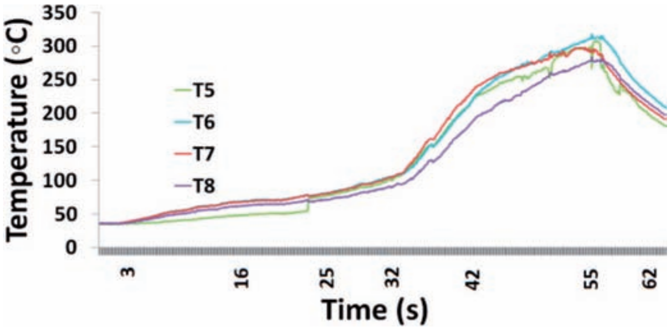

Fig. 6. Temperature changes during the plunge for each thermocouple at the surface

Table 3.
Maximum temperature measured and calculated at the end of the plunge in the points 5-8

Thermocouple position	**Maximum temperature (°C) Measured**
Point 5	308
Point 6	314
Point 7	297
Point 8	281

The macrostructure of the cross section is shown in Fig. 7. The whole of the cross section is divided into four parts, and the grains in each part have different size and orientation. The region located near the tool axis is characterized by microstructure consisting of very fine and randomly oriented grains (Fig. 8(a)). The main cause of microstructure changes in this region is severe plastic deformation. This region is called the stir zone. After stir zone, there is a region whose microstructure is affected by the mechanical deformation and temperature changes, and therefore it is called the thermo-mechanical affected zone (TMAZ). Grains are elongated in this zone, so that grain elongation represents the material flow during the process. Figure 8(b) shows the microstructures of the area, and grain elongations are shown with arrows. Dynamic recrystallization occurs in this area, and new grains are formed. In the vicinity of the TMAZ, the other region is formed in which the grains are formed just by the effect of temperature. This region is called the heat affected zone (HAZ) and static recrystallization mechanism affects the microstructure (Fig. 8(c)). Grains in the HAZ are larger than those in stir zone and TMAZ. Also, the elongation of the grains was not observed in this area. Finally, there is base metal, in the area where there is no change in the microstructure (Figure 8(d)).

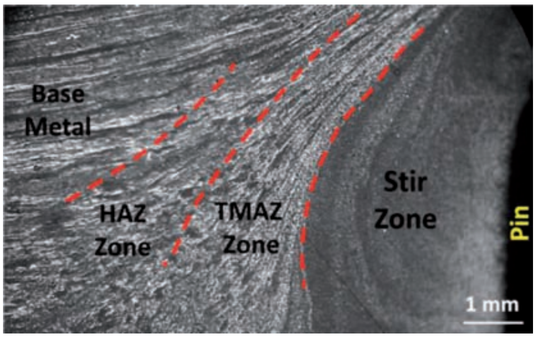

Fig. 7. The macro-structure of the plunge section (conducted at rotation speed 800 RPM)

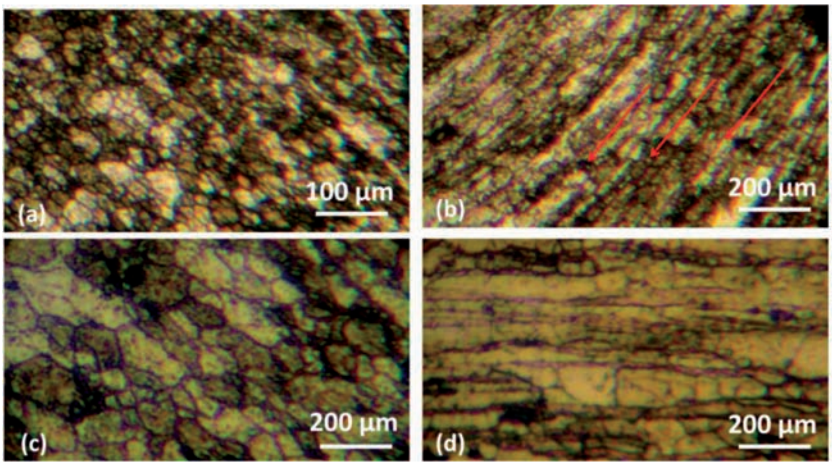

Fig. 8. The microstructure of the area in the: a) stir zone, b) TMAZ, c) HAZ, d) base metal (conducted at rotation speed 800 rpm)

4. Conclusion

FSW is widely used in the industry for manufacturing as a high quality construction method. To increase the quality of the manufacturing, a complete study on all aspects of this process sis inevitable. The plunge of the tool, as the initial stage of the FSW process, determines the initial conditions of the process, so is extremely important. The study on the plunge stage can also reveal useful information about friction stir spot welding process. The plunge stage has been studied by experimental methods to investigate the temperature distribution around the tool during the plunge stage. Work-piece temperature was measured during the process with proper tools. The temperature distribution around the tool was asymmetric. The temperatures of the points behind the tool were higher comparable with these at points located forward the tool. By increasing the distance from the tool, the rate of temperature equalization was decreased.

Microstructural observations indicate that macrostructural changes occurred in the workpiece, and four different zones (stir zone, TMAZ, HAZ and base metal) with different characteristics was formed. The ultra fine grains were the characteristics of the stir zone. In the TMAZ, grains that were elongated in the direction of material flow were observed. New grains are formed in the HAZ by static recrystallization mechanism. In the base metal, grains remain unchanged.

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Badania eksperymentalne rozkładu temperatury i mikrostruktury materiału w etapie zagłębiania procesu spawania tarciowego z przemieszaniem z wykorzystaniem narzędzia o trójkątnym trzpieniu

Streszczenie

Z uwagi na rozwojową rolę spawania tarciowego z przemieszaniem w przemyśle wytwórczym niezbędne jest całościowe badanie tego procesu. W szczególności, badania poszczególnych etapów procesu umożliwiają lepsze zrozumienie właściwości spawania tarciowego, zwłaszcza punktowego spawania tarciowego z przemieszaniem. W pracy badano metodami eksperymentalnymi etap zagłębiania w celu wyznaczenia rozkładu temperatury wokół narzędzia i zmian w mikrostrukturze elementu spawanego. Eksperymenty przeprowadzono na płytach z aluminium 7050, wykonując jednoczesne pomiary temperatury. W badaniach użyto narzędzia o trójkątnym trzpieniu. Wyniki badań są wykorzystane jako warunki początkowe dla teoretycznej analizy procesu spawania. Wyniki pokazują, że rozkład temperatury wokół narzędzia jest wyraźnie asymetryczny. Asymetria ta jest wynikiem nierównomiernego rozkładu nacisku pod narzędziem oraz pochylenia narzędzia pod określonym kątem. Temperatury w punktach poza narzędziem były wyższe niż te w punktach przed nim. Badania mikrostruktury ujawniły istnienie czterech obszarów, o różnych mikrostrukturach, które formują się wokół narzędzie w trakcie procesu. Obszary te wyróżniają się rozmiarami i kształtem ziaren. Ziarna w pobliżu narzędzia są wydłużone w określonym kierunku, który wskazuje kierunek płynięcia materiału.