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EFFECT OF SELECTED FRICTION STIR WELDING PARAMETERS ON MECHANICAL PROPERTIES OF JOINTS

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The article discusses the basic issues related to the technology of friction stir welding (FSW). A short description of technology is provided. The following section provides the analysis of effect of technological parameters (tool rotation and welding speed) on the mechanical properties of the prepared joint (strength, ductility, microhardness). In both cases the analysis refers to aluminum alloys (6056 and AA2195-T0). The comparative analysis showed the phenomenon of the increase in weld strength along with the increase in the rotational speed of the tool during welding. Similarly, with the increase in welding speed, an increase in weld strength was observed. Some exceptions have been observed from the above relations, as described in the article. In addition, examples of material hardness distribution in the joint are presented, indicating their lack of symmetry, caused by the rotational movement of the tool. The analyses were performed basing on the literature data.

Keywords: *friction stir welding (FSW), aluminum alloys, mechanical properties, material microstructure*

1. INTRODUCTION

Aluminum alloys can be used for various engineering purposes. Their major applications include structural load-bearing elements of bridges and buildings and non-structural elements, for example, exterior wall cladding systems. Aluminum alloys elements, like those made of steel, are generally

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joined by welding. The main problem, however, is lower thickness and therefore reduced strength of the material in the heat-affected zone (HAZ). This phenomenon can be prevented by increasing the weld thickness or using special weld washers to reinforce the weld area.

The most modern and innovative technology employed to join aluminum alloys is friction stir welding. This method demonstrates great potential for many engineering applications. This article gives an overview of the friction stir welding process and discusses the strength of aluminum alloy workpieces joined using this method.

2. FRICTION STIR WELDING

Friction Stir Welding (FSW) is a solid-state joining process, which allows full penetration of the weld with no melting involved. As the melting point is not reached, the process requires the conversion of kinetic energy to thermal energy by applying friction. This method is commonly used to join metallic materials, particularly aluminum and its alloys.

Friction welding is not a new process. It was patented more than a hundred years ago (1891) in England and since then it has been constantly developed. Crucial advancements in this field are reported to take place in Europe in the 1920s, the 1940s and the late 1950s. Today, the most common techniques are friction butt welding, conventional friction welding, inertia friction welding and, the latest, friction stir welding.

Friction stir welding was invented and patented in 1991 by The Welding Institute in Cambridge, UK [1]. The technique has been further developed, with the largest contributions being made by Japanese, American and European engineers. Many of the concepts are now used in various industrial sectors. The major areas of application are the automotive, aviation, tool, mining and power industries. FSW is also suitable for defense, rail transport, aerospace and civil engineering applications.

Friction welding techniques use thermal energy generated during friction and the resulting plasticization of the material to join the workpieces. In FSW, the rotating cylindrical tool with a locking shoulder and a penetrating pin traverses along the weld line intermixing the materials of the workpieces being joined. FSW requires employing holding fixtures to prevent any movement of the workpieces. While the rotating tool moves along the interface, it exerts mechanical pressure causing the abutting weld region to soften, plasticize and then coalesce. The material is moved towards the rear side of the tool, parallelly to the tool motion direction. Material consolidation behind the tool occurs. The schematic diagram of the friction stir welding process is shown in Fig. 1.

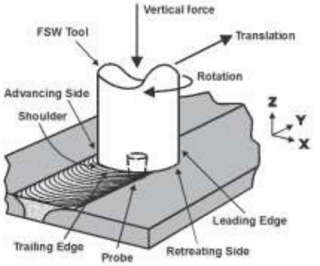


Fig. 1. Schematic diagram of the friction stir welding process [2]

Joints produced by friction stir welding are characterized by very high quality and high mechanical properties, especially high strength. As there is an increase in the material temperature and its plasticization at the interface, diffusion-inducing stresses occur. The grains in the dynamically recrystallized zone, where the materials have intermixed, are of an order of magnitude smaller than those in the unaffected material. Hence the high strength of the weld. The FSW technology enables obtaining high quality joints and limiting the amount of microdamage that can be the initiator of the material cracking process [3-6].

There are several parameters characteristic for the FSW process. These include the rotation speed, the tool geometry and dimensions, the welding speed and other. The welding speed and the tool rotation speed have a great effect on the welding process. The weld quality is largely dependent on the clamping of workpieces because the substantial forces and moments observed during FSW may be responsible for the occurrence of undesirable deformations.

Friction stir welding is primarily designed to butt join aluminum sheets, plates and sections, but it is also suitable for joining other materials, such as copper, magnesium, titanium or zirconium alloys as well as stainless steel or lead. The elements joined can be from 1.6 mm to 30 mm in thickness.

This method has a number of benefits making it superior to conventional fusion welding processes. The tool is able to fully penetrate the weld area in order to produce high quality, smooth welds, free from pores and air bubbles. The FSW method is well-suited to join different aluminum alloys, including the 2xxx, 5xxx, 6xxx, 7xxx and 8xxx series alloys, and alloys difficult to weld.

FSW technology is characterized by relatively low process temperature (in comparison to other welding techniques), which results in reduction in material shrinkage and welding stresses. The technology does not require the use of fillers and shielding gases, no fumes are produced during welding. The process is safe and ecological. Moreover, in the most applications the edge preparation is not needed (lower cost and shorter process duration). FSW is also reported to be repeatable and energy efficient technology [7].

There are many friction stir welding techniques, which differ in the process features, the tool design or the tool motion. This technology can be used to produce various weld types, especially butt welds and pipe welds.

The geometry of the tool has a large impact on both strength and the microstructural parameters of the finished joint [8-13]. In addition to the shape of the tools, there are many technological parameters affecting the properties of the joint. The most important of them are the tool rotation speed and travel speed. The goal of the present study is to discuss the effect of these two parameters on mechanical properties of joints, basing on the data derived from the literature [14, 15].

3. EFFECT OF TOOL ROTATION AND TRAVEL SPEED ON JOINT PARAMETERS

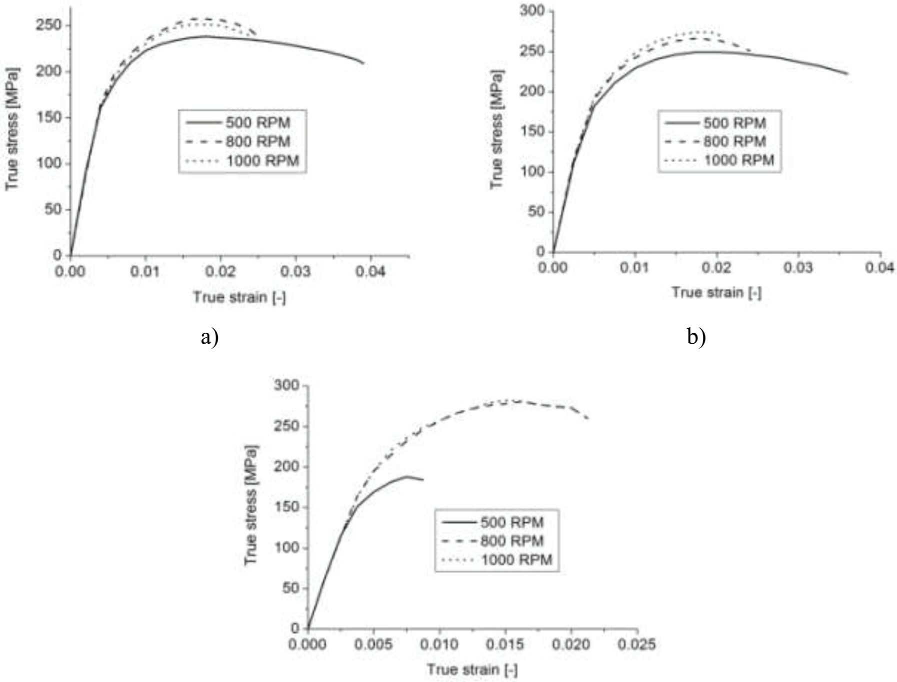
As reported in many papers, for example [14, 15], the speed of tool rotation and travel speed are the most important technological parameters, affecting the joint strength, ductility, hardness, as well as microstructure.

An interesting insight into this dependence is provided in [14]. The authors analyzed mechanical parameters and microstructure of joints produced by FSW in heat-treated 6056 aluminum. Plates of 4 mm thickness were welded along rolling direction, using tool rotation speed 500, 800 and 1000 RPM, and travel speed 40, 56 and 80 mm/min, i.e. the welding process was conducted for 9 sets of parameters. The joints were heat-treated in order to increase their corrosion resistance. This included heating at 170 °C for 6 h, water quenching, the next heating at 190 °C for 13 h and final water quenching.

The next step involved static tensile test of joints obtained using different tool rotation and travel speed. The specimens were prepared by cutting the welded plates perpendicularly to the welding direction. The stress-strain curves are given in Fig. 2 (three diagrams depending on tool travel speed). The comparative analysis of Figs. 2 a-c indicates effect of rotation and travel speed on the joint strength and ductility. In all the cases the lowest rotation speed (500 RPM) produced the lowest joint strength (from about 190 to 240 MPa), which is significantly different from the strength of the base material (316 MPa). On the other hand, the combination of low rotation speed with low and medium travel speed (40 and 50 mm/min) resulted in the highest joint ductility. This effect was not observed in the case of the highest travel speed (80 mm/min - see Fig. 2c).

Regardless of tool travel speed, the stress-strain curves of joints obtained using 800 and 1000 RPM show similar character. The differences in strength and ductility are slight. In these cases joints are characterized by high strength (up to ~280 MPa).

Changes in the weld mechanical behavior are believed to result from different material microstructures, dependent on the FSW process parameters. As indicated in [14, 16-18], the FSW process involves temperature-related precipitates dissolution and re-precipitation. As a result, there is a change in size and distribution of precipitates, which results in different material behavior in the range of hardening (precipitation hardening). As mentioned, the process of precipitates dissolution and re-precipitation depends on the temperature and the cooling rate, which, in turn, depend on the welding speed.



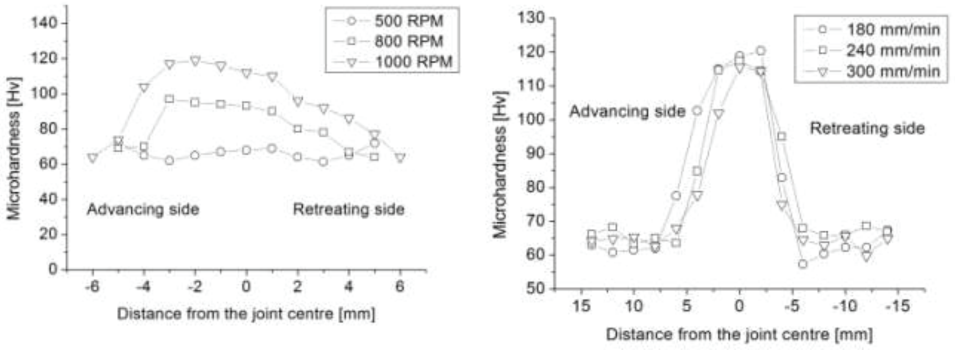
a) b)

c)

Fig. 2. Stress - strain curves obtained for FSW joints in 6056 aluminum alloy, depending on tool rotation and travel speed: a) travel speed 40 mm/min, b) 56 mm/min, c) 80 mm/min, basing on [14]

According to [14, 19-21], reduction in the grain size results in higher material ductility. In the analyzed cases, no monotonic relationship between the considered welding parameters (both travel and rotational speed) and the grain size was found, hence for the 800 and 1000 RPM rotational speed, the weld ductility was similar in each analyzed case. Considering the above, it is difficult to explain the significant difference in strain-to-failure of weld materials made at 500 RPM (depending on the linear speed from approx. 0.9 to 3.8%).

Authors [14] also analyzed the effect of tool rotation speed on the distribution of hardness in weld cross section. An example of results obtained for travel speed 40 mm/min is presented in Fig. 3a. As previously, three rotation speeds were taken into consideration (500, 800 and 1000 RPM). The comparative analysis of charts indicates that increase in tool rotational speed results in higher weld microhardness. In case of the lowest rotation speed, microhardness distribution is uniform. Significantly greater differences can be observed in the case of higher tool rotation speeds.



a) b)

Fig. 3. Microhardness distribution in the joint: a) an exemplary distribution of FSW joint microhardness, obtained for travel speed 40 mm/min and 3 rotation speeds – 500, 800 and 1000 RPM (0 on the "distance" axis denotes weld center), basing on [14], b) effect of FSW tool travel speed on microhardness distribution in the weld cross section for AA2195-T0 alloy, basing on [15]

According to the authors' suggestions [14], as well as other researchers' cited by them [16, 22], the increase in the hardness of the material in the area of the weld nugget should be explained by the changes that take place in the structure and distribution of precipitations during welding. As mentioned above, this process depends on the temperature distribution during welding, and thus also indirectly on the rotational speed of the tool. Hence, a significant influence of the rotational speed on the weld hardness is visible in Fig. 3a.

In addition, it is worth noting that the hardness distribution is not symmetrical with respect to the center of the weld (distance “0” on the graph). This is due to the rotational movement of the tool. The authors of the study noticed that the greater hardness occurred on the advancing side of the tool.

For higher travel speeds (56 and 80 mm/min) authors obtained similar relationships, but in these two cases the differences were smaller.

Analysis of the effect of travel speed on the distribution of microhardness in the cross-section of the weld was carried out by the authors of [15]. Butt-joints made on aluminum alloys (AA2195-T0 and AA2195-T8) were tested. Plates 7.6 mm in thickness were welded along the rolling direction. Similarly to the previous work, various welding parameters were used (rotational speeds in the range from 350 to 800 RPM and welding speeds from 120 to 360 mm/min).

Fig. 3b presents an example diagram of microhardness distribution in the weld cross-section depending on the travel speed (data on the graph refers to the rotational speed of 600 RPM). As can be seen in the figure, increasing the speed of welding causes a decrease in the micro-hardness of the weld. It is worth noting that the hardness of parent material is 63.7 Hv.

In comparison to Fig. 3a, the graph in Fig.3b is characterized by significantly better symmetry, i.e. there are no meaningful differences in hardness between advancing and retreating side. Although in this case the welding speed was significantly higher than previously, symmetrical hardness distributions are also obtained at low speeds [23-25].

Furthermore, the comparison of diagrams in Figs. 3a and 3b indicates that the travel speed had less impact on hardness than the rotational speed of the tool.

4. CONCLUSIONS

Both strength and the microstructural parameters of the FSW weld depend very strongly on the technological parameters, especially the rotational speed of the tool and the travel speed. As demonstrated in the article, weld strength as well as its ductility and hardness depend on both of these parameters. The most conspicuous is the dependence between the rotational speed of the tool and the hardness of the material in the weld axis for a travel speed of 40 mm/min in heat-treated 6056 aluminum (Fig. 3a). The relationship can be described by an empirical formula in the form:

$$Hv = 0.088\omega + 23.82$$

where:
Hv – material hardness in the joint centre (distance "0" in Fig. 3a), ω – rotational speed of the tool [RPM] at fixed travel speed 40 mm/min

Structural aluminum alloys used in construction in accordance with the standard [26] can also be subjected to the FSW process. As demonstrated in [27, 28], also in this case the rotational speed of the tool affects the mechanical properties of the joint, in particular its hardness and strength. Tests carried out on similar and dissimilar aluminum joints (5xxx, 6xxx, 7xxx) showed a slight decrease in the weld strength along with the increase in the rotational speed of the tool, which is the opposite trend to the one presented in this article. It is presumed that this may result from a different material structure as well as from other linear and rotational speed ranges used by the authors.

Regardless of the observations described above, attention should be paid to processes occurring in the heat affected zone (HAZ) [29, 30]. Thermal phenomena taking place in this area cause a change in the material microstructure, which has a direct impact on its strength properties. The key of importance are over-age and re-dissolution of hardening precipitates. Therefore, the authors of [29, 30] observed reduced strength of material in the HAZ zone.

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LIST OF FIGURES

WPŁYW WYBRANYCH PARAMETRÓW ZGRZEWANIA TARCIOWEGO NA WŁAŚCIWOŚCI MECHANICZNE SPOINY

Słowa kluczowe: zgrzewanie tarciowe z przemieszaniem (FSW), stopy aluminium, parametry mechaniczne, mikrostruktura materiałowa

STRESZCZENIE:

W artykule przedstawiono podstawowe zagadnienia związane z wpływem wybranych parametrów technologii zgrzewania tarciowego (prędkość obrotowa i liniowa narzędzia) na właściwości mechaniczne gotowej spoiny, ze szczególnym uwzględnieniem zależności naprężenie-odkształcenie i twardości materiału.

Technologia zgrzewania tarciowego z przemieszaniem (ang. *Friction Stir Welding – FSW*) jest coraz szerzej stosowana w połączeniach elementów aluminiowych nie tylko w przemyśle chemicznym, lotnictwie i motoryzacji, ale również w elementach konstrukcji budowlanych. Biorąc pod uwagę rosnący udział wykorzystania aluminium, należy spodziewać się, że technologia zgrzewania tarciowego będzie w przyszłości zdobywać coraz większą popularność na rynku.

Pierwsze próby wykonywania spoin z wykorzystaniem zjawiska tarcia miały miejsce pod koniec XIX w. Od tego czasu technologia jest stale rozwijana. Szczególny postęp dokonał się w latach 20 oraz na przełomie lat 40 i 50 XX w. Metoda zgrzewania tarciowego z przemieszaniem materiału, której dotyczy niniejszy artykuł, została opatentowana w Wielkiej Brytanii w roku 1991. Wykorzystuje się ją do zgrzewania materiałów trudno spawalnych przy użyciu tradycyjnych metod, to znaczy stopów aluminium, miedzi i innych.

Metoda zgrzewania tarciowego z przemieszaniem wykorzystuje energię cieplną wytworzoną przez ruch obrotowy narzędzia, przesuwającego się wzdłuż krawędzi łączonych elementów. Wzrost temperatury spajanych części powoduje zmiękczenie materiału, co umożliwia jego przemieszanie i utworzenie zgrzeiny. Należy zaznaczyć, że w technologii FSW materiał nie osiąga temperatury topnienia. Prawidłowe wymieszanie materiału umożliwia specjalna konstrukcja obracającego się narzędzia, złożonego z trzpienia i kołnierza. Technologia FSW wymaga unieruchomienia łączonych części tak, aby możliwe było wywołanie znacznego nacisku narzędzia na łączone krawędzie, a co za tym idzie zwiększenie siły tarcia.

Uzyskane w ten sposób zgrzeiny odznaczają się wysoką jakością, brakiem pustek i innych defektów struktury, co wiąże się również z wysokimi parametrami wytrzymałościowymi. Spoiny cechują się ponadto wysoką powtarzalnością. Spajanie nie wymaga znacznych nakładów energii ani wykorzystywania gazów osłonowych, co pozwala zakwalifikować zgrzewanie tarciowe do metod ekologicznych. Stosunkowo niska, w porównaniu do innych metod, temperatura ogranicza skurcz spoiny i naprężenia spawalanicze.

Jakość uzyskanej spoiny zależy od wielu parametrów technologicznych, przede wszystkim kształtu narzędzia, jego prędkości obrotowej, prędkości zgrzewania (ruch liniowy narzędzia) i innych. Warto zaznaczyć, że nadmierna prędkość spajania może skutkować obniżeniem jakości spoiny, powstaniem jej defektów, a w skrajnym przypadku tzw. zjawiska tunelowania, to znaczy powstania liniowego defektu wzdłuż spoiny.

Przedstawione powyżej parametry technologiczne procesu zgrzewania tarciowego (przede wszystkim prędkość obrotowa i liniowa narzędzia) mają zasadniczy wpływ na właściwości mechaniczne (wytrzymałość, ciągliwość, twardość) gotowej spoiny.

W pracy [14] omówiono zależność parametrów mechanicznych i mikrostruktury zgrzeiny od prędkości obrotowej i liniowej narzędzia. Badania wykonywano na złączach blach o grubości 4 mm, wykonanych ze stopu aluminium 6056 i

poddanych obróbce termicznej. Zastosowano prędkości obrotowe narzędzia o wartościach 500, 800 i 1000 obr./min oraz prędkości liniowe 40, 56 i 80 mm/min, dzięki czemu zgrzewanie przeprowadzono dla 9 zestawów parametrów technologicznych.

Z przygotowanych elementów, w kierunku poprzecznym do osi spoiny, wycinano próbki do badań wytrzymałościowych. Przeprowadzono standardową, statyczną próbę rozciągania, w celu określenia zależności naprężenie-odkształcenie dla każdej z otrzymanych spoin. Stwierdzono, że zarówno prędkość obrotowa jak i liniowa narzędzia mają istotny wpływ na wytrzymałość i ciągliwość złączy. Zastosowanie najniższej prędkości obrotowej (500 obr./min) skutkowało uzyskaniem najniższej wytrzymałości złącza (zależnie od prędkości liniowej od 190 do 240 MPa), co jest wartością zdecydowanie niższą od wytrzymałości materiału rodzimego (316 MPa). Z kolei kombinacja najniższej prędkości obrotowej z niską i średnią prędkością liniową (odpowiednio 40 i 56 mm/min) pozwoliła na uzyskanie wysokiej ciągliwości materiału zgrzeiny.

Zróżnicowanie parametrów mechanicznych zgrzein należy tłumaczyć ich zmianami mikrostrukturalnymi, związanymi z rozkładem temperatury podczas spajania, który z kolei jest zależny od prędkości obrotowej i liniowej narzędzia. Zgrzewaniu tarciowemu towarzyszy bowiem rozpuszczanie i ponowne wytrącanie wydzieleń, co powoduje przekształcenie struktury materiału i zmianę jego właściwości. Przebieg procesu nagrzewania i studzenia materiału skutkuje ponadto zróżnicowaniem wielkości ziaren, która determinuje ciągliwość materiału.

Autorzy pracy [14] analizowali ponadto wpływ prędkości zgrzewania na rozkład twardości materiału w przekroju poprzecznym zgrzeiny. Zaobserwowano, że wzrostowi prędkości obrotowej narzędzia towarzyszy wzrost twardości materiału zgrzeiny. Co więcej, w przypadku najniższej prędkości obrotowej (500 obr./min), rozkład twardości w przekroju poprzecznym spoiny jest jednorodny, brak jest znaczących różnic twardości pomiędzy jądrem zgrzeiny a strefą wpływu ciepła. Zależność ta nie miała zastosowania do zgrzein wykonanych z zastosowaniem prędkości 800 i 1000 obr./min, gdzie twardość materiału w przekroju poprzecznym zgrzeiny może różnić się blisko dwukrotnie. Tak jak poprzednio, autorzy pracy wskazują na przemiany mikrostrukturalne zachodzące w materiale jako źródło różnic twardości materiału.

Jak zauważono, rozkład twardości w przekroju poprzecznym nie jest symetryczny, co jest spowodowane wpływem ruchu obrotowego narzędzia.

Wpływ prędkości liniowej narzędzia na twardość materiału w zgrzeinie opisali autorzy pracy [15]. Analiza przeprowadzona na zgrzeinach stopów aluminium AA2195-T0 i AA2195-T8 wykazała niewielką zależność pomiędzy wymienionymi wyżej parametrami.

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