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FRACTURE TOUGHNESS OF FRICTION STIR WELDED JOINTS OF AlCu$_4$SiMg ALUMINIUM ALLOY

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The objective of paper was to determine the fracture toughness of friction stir welding (FSW) joints of EN AW-2014 (AlCu$_4$SiMg) aluminium alloy, and to compare the fracture toughness of FSW with that of conventional metal inert gas (MIG) process. FSW of aluminium alloy was performed on a conventional semiautomatic milling machine. Defect free FSW welds were produced on alloy plates at constant tool rotation and traverse speed of 1600 rpm and 200 mm/min, respectively. The results of Vickers hardness and Charpy impact tests were used to evaluate the fracture toughness of welded joints. Low heat input, absence of melting and filler metal resulted in better fracture toughness for FSW joints.

Key words: *friction stir welding, friction welding, aluminium, fracture toughness*

Lomna žilavost trenjem zavarenih spojeva iz AlCu$_4$SiMg aluminijske legure. Cilj rada je odrediti lomnu žilavost trenjem zavarenih spojeva (FSW) aluminijske legure EN A W-2014 (AlCu$_4$SiMg) te usporediti lomnu žilavost dobivenu zavarivanjem trenjem s onom nakon konvencionalnog zavarivanja u zaštiti inertnim plinom (MIG postupak). Zavarivanje trenjem aluminijske legure provedeno je konvencionalnim poluautomatskim uređajem. Zavarivanje trenjem dobiveni su zavari bez grešaka na limovima kod stalnog kkretaja alata od 1600 o/min i kod brzine od 200 mm/min. Za ocjenu lomne žilavosti zavarenih spojeva rabljeni su rezultati ispitivanja tvrdoće Vickeras metodom i udarne energije Charpy metodom. Nizak unos topline, odsutnost taljenja i dodatnog metala rezultiralo je u boljoj lomnoj žilavosti trenjem zavarenih spojeva.

Ključne riječi: *gibajuće zavarivanje trenjem, zavarivanje trenjem, aluminij, lomna žilavost*

INTRODUCTION

Light weight aluminium alloys with high specific strength are widely used in industry [1]. Chemical and physical properties of aluminium influence its welding characteristics, although there are different techniques used to join this alloy. The specific properties that affect the welding of aluminium and its alloys are its oxide characteristics, the solubility of hydrogen in molten aluminium, its thermal, electrical and nonmagnetic characteristics, lack of colour change when heated, its alloys, wide range of mechanical properties and melting points [2, 3]. Traditional welding process application to Al alloys present a series of disadvantages that have sometimes discouraged the use of such a kind of welded materials. Friction stir welding assures the absence of porosity, distortion and residual stresses which are typical defects of the fusion welding processes [3]. FSW process offers a new, low cost alternative to fusion welding processes due to low power requirements, no gas shielding and no special joint edge preparation [4, 5]. The process can be used in conjunction with conventional milling machines and does not produce any major safety hazards such as fume or radiation [6]. In FSW applications, a non-consumable tool which is manufactured from various materials with superior high temperature properties to those of the materials to be joined is employed with various designs [7]. The FSW tool has, a profiled pin which is obtained in a shoulder with a larger diameter than that of the pin as seen in Figure 1. Frictional heating between the tool and material generate sufficient heat to locally politicise the aluminium alloy to be welded. Tool rotation during the FSW process imparts a three dimensional material flow to the plasticised weldment, thus causing complete mixing of the alloy [7, 8]. The plates to be welded are secured to prevent the butted joint faces

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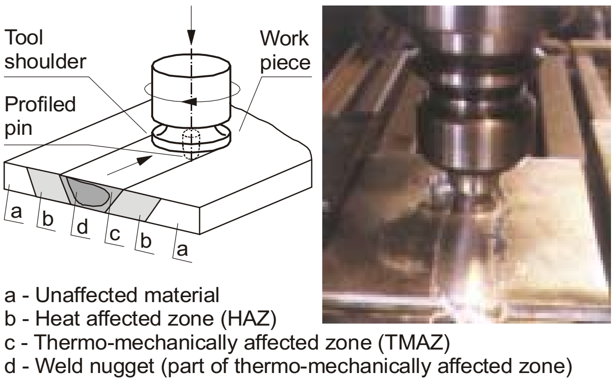


Figure 1. **a) Schematic illustration of friction stir welding process and microstructure of heat-affected zone [4], b) FSW application on conventional milling machine**
Slika 1. **a) Shematski prikaz procesa zavarivanja trenjem gibanjem i mikrostrukture zone utjecaja topline [4], b) Uobičajena primjena FSW postupka zavarivanja**

from being forced apart as the probe passes through and along the seam [9]. For thick plate welding (25 to 50 mm thickness) usually a pilot hole, smaller in diameter than the probe itself, is drilled at the start to assist the plunging operation [8]. The depth of penetration is controlled by the length of probe below the shoulder of the tool [10]. The initial plunging friction contact heats the adjacent metal around the probe as well as the small region of material underneath the probe, but once in the contact with the top surface of the substrate the shoulder contributes significant additional heat to the weld region [2, 11]. In addition the contacting shoulder which can be profiled to provide improved coupling, prevents highly plasticised material being expelled from the welding region [12]. Once the rotating tool is in its position, the thermally softened and heat-affected zone takes up a shape corresponding to that of the overall geometry [9, 13, 14]. The heat-affected zone, which is much wider at the top surface (in contact with the shoulder), tapers down as the probe diameter reduces [15]. The combined frictional heat from the probe and the shoulder creates a highly plasticised "third body" condition around the immersed probe and the adjacent contacting surface of workpiece [3]. This highly plasticized material provides for some hydrostatic effect as the rotating tool moves along the joint which helps the plasticized material to flow around the tool [15,16]. The pin is traversed trough the joint line while the shoulder is intimate contact with the top surface of the workpiece to avoid expelling softened material [17, 18]. The basic variants of FSW tools are given in Figure 2.

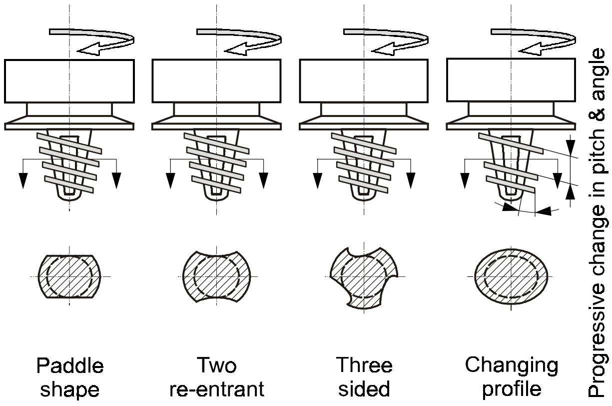


Figure 2. **Basic variants of FSW tools [6]**
Slika 2. **Osnovne inačice FSW alata [6]**

Materials develop plastic strains as the yield stress exceeds in the region near the crack tip. The amount of plastic deformation is restricted by the surrounding material which remains elastic. The size of the created plastic zone depends upon the stress conditions of the structure. If the stress intensity factor reaches a critical value K_C, unstable fracture occurs. The fracture toughness of a material is characterized by the energy per unit area which is required to create new crack surfaces, and thereby propagate a crack through the material. The fracture toughness is dependent on specimen geometry, metallurgical factors and temperature. This critical value of the stress intensity factor K_C is known as the fracture toughness of the material. Basic fracture modes are given in Figure 3. This parameter is extensively used to design fracture safe structures.

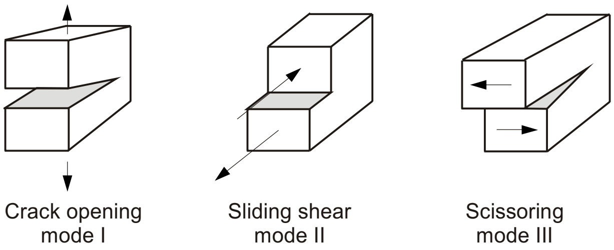
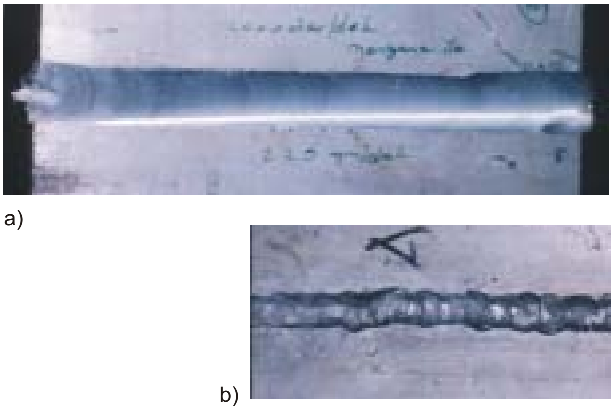


Figure 3. **Basic fracture modes**
Slika 3. **Osnovni modeli prijeloma**

In the present study the fracture toughness of the friction stir welded EN AW-2014 (AlCu$_4$SiMg) Al alloy joints were evaluated. The fracture toughness of FSW joints is also compared with that of conventional MIG welded joints. The fracture toughness values of joints were calculated according to Mode I. The Mode I fracture toughness of a material usually depends on the orientation and direction of propagation of the crack in relation to the anisotropy of the material which depends on principal directions of mechanical working or grain flow.

EXPERIMENTAL STUDIES

The materials used in this study was commercial EN AW-2014 (AlCu$_4$SiMg) Al alloy. Welding direction was perpendicular to the rolled direction of the aluminium plates. The diameter of the tool shoulder was 20 mm, and the diameter of insert pin and height were 5 and 5 mm respectively. During the experimental studies, friction stir welds were carried out at constant tool rotation and transverse speed of 1600 rpm and 200 mm/min, respectively. Double sided FSW was applied to the specimens. The specimens to be welded were machined out from 10 mm thick plates having dimensions of 125 mm width and 200 mm length. FSW was carried out using a semiautomatic milling machine. Typical surface appearance of FSW was a regular series of partially circular ripples, which points towards the start of the weld as seen in Figure 4. These ripples were essentially cycloidal and were produced by the final sweep of the trailing circumferential edge of the shoulder. The surface of the FSW welds were similar with the surfaces that roughly milled. The surface colour of the FSW was silvery-white for studied Al alloy as seen in macrograph given in Figure 4.


a)

b)

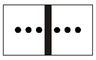
Figure 4. **Surface macrograph of FSW (a) and MIG welds (b)**
Slika 4. **Makrografija ploštine FSW (a) i MIG zavara (b)**

Another set of Al alloy plates were butt welded (two sided I - joint) with the MIG process in which the rolling direction of the plates were perpendicular to the direction of the weld run. The plates were prepared and cleaned with a scraper and acetone before welding. MIG – 350 type semiautomatic welding machine was used for welding the plates with the parameters of 240 ± 10 A (current) and 24 ± 1 V (voltage). The MIG welds were carried out by using 2319 filler wire of 1,2 mm diameter with a welding speed of 60 mm·min^{-1}. Shielding was provided by argon gas at a flow rate of 18 l·min^{-1}. To evaluate the fracture toughness of EN AW-2014 (AlCu$_4$Si Mg) aluminium alloy, Charpy impact and Vickers hardness tests were carried out on the welded joints where 20 kg load was used in Vickers hardness tests. Charpy impact tests with V-notch were performed according to EN 10045-1 at room temperature. Hardness tests were made on the surface of welded plates perpendicular to weld seam and along a line drown on the cross section of the weld. The results of the Charpy impact and Vickers hardness tests were used to calculate and evaluate fracture toughness of the welded joints.

RESULTS AND DISCUSSION

Charpy impact and Vickers hardness tests were applied to base metal, FSW and MIG welded joints respectively. The results of Vickers hardness and Charpy impact tests are given in Table 1. The Charpy impact energy of FSW is only 6 % lower than that of parent material and 16 times greater than that of the MIG welded specimens. Better impact resistance of FSW joints compared to that of MIG can be explained with "stirring" effect of FSW process which results in finer microstructure [4, 19]. In contrast, MIG welds have a coarse columnar crystalline structure with lower impact resistance property [20, 21]. The results of the hardness tests show that the length of hardness reduction on the line perpendicular to weld seam of FSW is shorter than MIG. This observation can be explained with less amount of energy input in FSW welded specimens which results in smaller heat-affected zone [22, 23].

Table 1. **The results of Vickers hardness and Charpy impact tests of FSW and MIG welds**
Tablica 1. **Rezultati ispitivanja tvrdoće Vickers metodom i energije udara Charpy metodom za FSW i MIG zavare**

<table>
<tr><td colspan="14">Charpy Impact Test Results</td></tr>
<tr><td colspan="5"></td><td colspan="3">Base metal</td><td colspan="3">FSW</td><td colspan="3">MIG</td></tr>
<tr><td colspan="5">KV / J</td><td colspan="3">100</td><td colspan="3">94</td><td colspan="3">6</td></tr>
<tr><td colspan="14">Vickers Hardness Test Results (HV)</td></tr>
<tr><td rowspan="3">On the surface of the weld

–25 0 25</td><td>Distance from weld centre / mm</td><td>25,0</td><td>20,0</td><td>15,0</td><td>10,0</td><td>2,5</td><td>5,0</td><td>–2,5</td><td>–5,0</td><td>–10,0</td><td>–15,0</td><td>–20,0</td><td>–25,0</td></tr>
<tr><td>FSW HV$_{20}$</td><td>45,5</td><td>45,5</td><td>44,0</td><td>39,3</td><td>38,1</td><td>37,2</td><td>35,0</td><td>35,2</td><td>38,6</td><td>42,3</td><td>44,0</td><td>45,5</td></tr>
<tr><td>MIG HV$_{20}$</td><td>37,7</td><td>37,2</td><td>37,2</td><td>29,5</td><td>36,0</td><td>42,3</td><td>37,7</td><td>42,3</td><td>34,6</td><td>34,6</td><td>37,2</td><td>37,7</td></tr>
<tr><td rowspan="2">On the cross section of the weld

–25 0 25</td><td>FSW HV$_{20}$</td><td>54,3</td><td>54,3</td><td>51,5</td><td>41,1</td><td>35,0</td><td>31,3</td><td>35,0</td><td>46,0</td><td>51,5</td><td>51,5</td><td>54,0</td><td>54,3</td></tr>
<tr><td>MIG HV$_{20}$</td><td>37,7</td><td>38,6</td><td>38,2</td><td>32,2</td><td>37,7</td><td>36,8</td><td>32,8</td><td>34,0</td><td>35,9</td><td>38,6</td><td>40,5</td><td>40,5</td></tr>
</table>

Fracture toughnesses of welded joints were calculated using the experimental results of Charpy impact and Vickers hardness tests. The evaluation of fracture toughness of weld joints were made according to Mode I. Variation of the fracture toughness as a function of distance from the weld centre of joints on the surface of the plates are given in Figure 5., and that the for the cross section of the plates in Figure 6. Fracture toughnesses of base metal, FSW and MIG joints shown in Figures 5. and 6. were calculated by using the following equation.

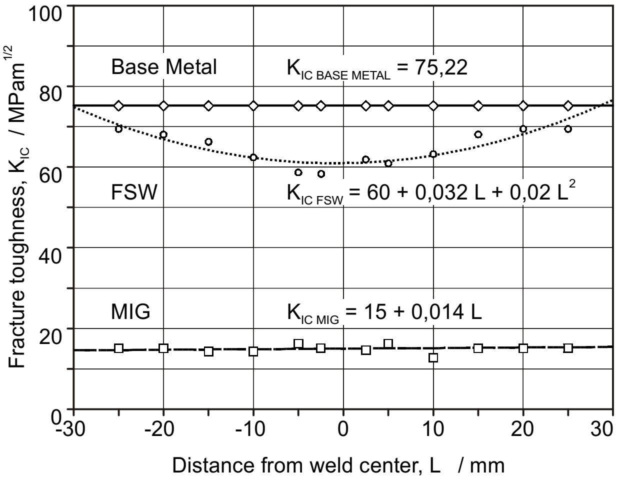


Figure 5. **Variation of the fracture toughness as a function of distance from the weld centre of joints on the surface of the plates**

Slika 5. **Promjena lomne žilavosti na popvršini lima o udaljenosti od centra zavarenog spoja**

$$[K_{IC} / R_e]^2 = 0,59\ [(CVN / R_e) - 0,0043] \qquad (1)$$

Where K_{IC} is the fracture toughness of the material according to Mode I [22, 23], *Re* is the yield strength of material and *CVN* is the Charpy impact energy of V notched specimens. For soft and ductile materials like aluminium alloys, it may not be easy to determine the exact position on the stress-strain curve where yielding occurs because the slope of the straight (elastic) portion of the curve begins to decrease slowly [24]. Therefore, the yield strength of studied Al alloy was calculated from the equation (2) developed by Voort [25] for Al alloys.

$$0,2\ \%\ R_e = 0,148\ HV - 1,59 \qquad (2)$$

As seen from the Figures 5. and 6. FSW joints have higher fracture toughness than MIG joints. Even though the fracture toughness of FSW joints is 20 % lower than parent material it is 3,75 times higher than MIG joints. Comparison of Figures 5. and 6. also imply that fracture toughness reduction depends upon the part of the material affected by friction, stirring effects and heat. The most reduction in fracture toughness of FSW were come out at the centre of the FSW welds, i.e. at the interface of the butted plates as seen in Figures 5. and 6. Comparison of Figure 5. and 6. indicate that the geometric dimension of the heat-affected zone (HAZ) is maximum at the surface of the material (at the interface of the tool shoulder and material) and minimum at the tool pin tip due to the nature of FSW phenomenon. This conclusion dictate us that the region where fracture toughness is reduced, can be controlled by optimising the geometric dimensions of FSW tool.

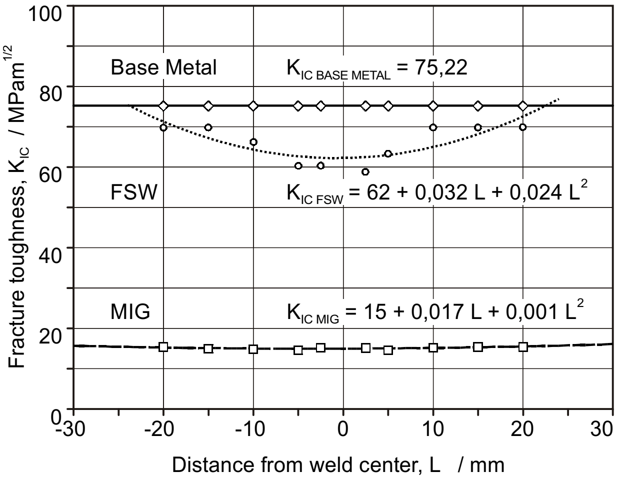


Figure 6. **Variation of the fracture toughness as a function of distance from the weld centre of joints at the cross section of the welds**

Slika 6. **Promjena lomne žilavosti kroz poprečni presjek zavara o udaljenosti od centra zavarenog spoja**

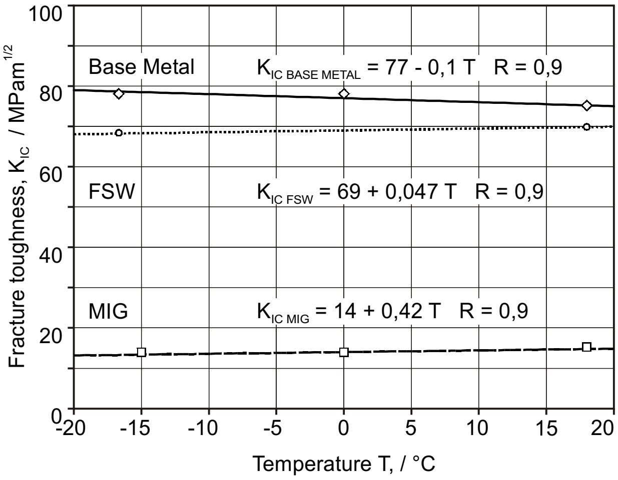


Figure 7. **The effect of the heat on the fracture toughness of FSW and MIG joints**

Slika 7. **Utjecaj topline na lomnu žilavost FSW i MIG zavara**

The effect of heat on the fracture toughnesses of the FSW and MIG joints is shown in Figure 7. The fracture toughnesses of the FSW and MIG joints at 20 °C specimen temperature are higher than the specimens which tested at lower specimen temperatures. Improvement in the fracture toughness of the joints at higher temperatures can be explained with the increase in ductility and toughness at elevated temperature.

CONCLUSION

From the above mentioned experimental results it can be concluded that the stirring effect of FSW results in finer microstructure and better fracture toughness than conventional gas metal arc welding process.

Detectably large difference between the fracture toughness values of FSW and MIG joints is due to the coarse columnar crystalline structure of MIG joints compared to that of FSW.

On the other hand the difference between the fracture toughnesses of the base metal and FSW joints depends on material affected form friction, stirring and heat.

The critical fracture toughness region of FSW joints is the interface of the butted plates.

The geometric dimensions of the region of FSW joints where fracture toughness reduces can be controlled by optimising the dimensions of the FSW tool.

As a solid phase joining process with lower temperature regimes than fusion techniques, FSW eliminates the problems encountered with liquid phase joining processes.

REFERENCES

[1] A. Eksi, M. K. Kulekci, Metalurgija, 43 (2004) 2, 129 - 134.
[2] M. Cabibio, E. Meccia, E. Evangelista, Materials Chemistery and Phisics, 81 (2003), 289 - 292.
[3] M. K. Kulekci, Kovove Materialy, 41 (2003) 2, 97 - 105.
[4] W. M. Thomas, P. L. Threadgil, E. D. Nicholas, Science and Technology of Welding and Joining, 4 (1999), 365 - 372.
[5] T. Sohonida, Y. Kondoh, Journal of the JFWA, 2 (1995), 124 - 129.
[6] W. M. Thomas, R. E. Andrews, High Performance Tools For Friction Stir Welding. International Patent Application, WO 99/52669.
[7] W. M. Thomas, K. I. Jhonson, C. S. Wiesner, Advanced Engineering Materials, 5 (2003), 485 - 490.
[8] R. E. Andrews, J. S. Mitchel, Metals and Materials, 27 (1990), 796 - 801.
[9] M. Ericsson, R. Sandstrom, International Journal of Fatigue 25 (2003), 1379 - 1387.
[10] W. M. Thomas, E. D. Nicholas, Materials and Design, 18 (1997) 4/6, 269 - 273.
[11] P. J. Haagensen, O. T. Midling, M. Ranes, Computional Mechanics Publications, (1995), 225 - 237.
[12] W. B. Lee, Y. M. Yeon, S. B. Jung, Materials Science & Engineering A, 355 (2003), 154 - 159.
[13] W. B. Lee, Y. M. Yeon, S. B. Jung, Scripta Materialia, 49 (2003), 423 - 428.
[14] T. L. Dickerson, J. Przydatek, International Journal of Fatigue 25 (2003), 1399 - 1409.
[15] R. A. Prado, L. E. Murr, K. F. Soto, J. C. McClure, Materials Science & Engineering A, 355 (2003), 156 - 165.
[16] L. Cederquist, A. P. Reynolds, Welding Journal, December (2001), 281 - 287.
[17] C. G. Rhodes, W. M. Mahoney, W. H. Bingel, Scripta Materialia 36 (1997) 1, 69 - 75.
[18] K. Colligan, Welding Journal, 78 (1999) 7, 229 - 237.
[19] B. Irwing, Welding Journal, 76 (1997) 1, 31 - 41.
[20] M. K. Kulekci, Makina Tasarým ve Ýmalat Dergisi, 6 (2004)1, 13 - 18.
[21] M. K. Kulekci, A. Sýk, Suleyman Demirel Universitesi Fen Bilimleri Enstitusu Dergisi, 7 (2004) 3, 93 - 101.
[22] R.W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials, John Wiley and Sons, 1993, pp. 339 - 340.
[23] S. Maropoulos, N. Ridley, J. Kechagias, S. Karagiannis, Engineering Fracture Mechanics, 71 (2004), 1695 - 1704.
[24] S. Kalpakjian, Manufacturing Engineering Technology, USA, 1995, 63 - 65.
[25] G. F. V. Voort, Metallography Principles and Practice, ASM, 2000, 392 - 393.

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