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THE TENSILE BEHAVIOUR OF FRICTION-STIR-WELDED DISSIMILAR ALUMINIUM ALLOYS

NATEZNE ZNAČILNOSTI TORNIH POMIČNIH ZVAROV RAZLIČNIH ALUMINIJEVIH ZLITIN

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Aluminium alloys generally have a low weldability with the traditional fusion-welding process. However, the development of Friction Stir Welding (FSW) has provided an alternative, improved way of producing aluminium joints, in a faster and more reliable manner. The FSW process has several advantages, in particular the possibility to weld dissimilar aluminium alloys. This study focuses on the tensile behaviour of dissimilar joints of AA6351-T6 alloy to AA5083-H111 alloy produced by friction stir welding. Five different tool pin profiles, such as Straight Square (SS), Tapered Square (TS), Straight Hexagon (SH), Straight Octagon (SO) and Tapered Octagon (TO), with three different welding speeds (50 mm/min, 63 mm/min, 75 mm/min) have been used to weld the joints. The effect of the pin profiles and the welding speed on the tensile properties was analyzed and it was found that the straight square pin profile with 63 mm/min produced a better tensile strength then the other tool pin profiles and welding speeds.

Key words: friction stir welding, aluminium alloys, tool pin profile, welding speed, tensile properties

Aluminijeve zlitine so slabo varive po tradicionalnih talilnih postopkih. Razvoj tornega pomičnega varjenja (FSW) je ponudil možnost priprave aluminijevih zvarov na hiter in zanesljiv način. Proces ima več prednosti, predvsem možnost varjenja različnih aluminijevih zlitin. Raziskava je bila osredinjena na natezno vedenje različnih zvarov zlitin AA6351-T6 in AA5083-H111, pripravljenih s tornim pomičnim varjenjem. Pet različnih profilov trna je bilo uporabljenih: raven kvadrat (SS), koničen kvadrat (TS), raven šestkokotnik (SH), raven osemkotnik (SO) in koničen osemkotnik (TO) s tremi različnimi hitrostmi varjenja (50 mm/min, 63 mm/min in 75 mm/min). Določen je bil vpliv oblike trna in hitrosti varjenja na natezne lastnosti. Ugotovljeno je, da raven kvadraten trn pri hitrosti 63 mm/min da boljšo trdnost kot drugi profili trna in druge hitrosti varjenja.

Ključne besede: pomično torno varjenje, aluminijeve zlitine, profil tornega trna, hitrost varjenja, natezne lastnosti

1 INTRODUCTION

Friction stir welding (FSW) is a solid-state welding process developed by The Welding Institute (UK) in 1991, and now being used increasingly for joining aluminium alloys, for which fusion welding is often difficult. FSW uses a rotating tool with a probe travelling along the weld path, and plastically deforms the surrounding material to form the weld. Since the material subjected to FSW does not melt and recast, the resultant weld offers advantages over conventional fusion welds, such as less distortion, lower residual stresses and fewer weld defects.[1–3] When developing such a technology, one of the most important factors is the possibility to join different aluminium alloys. [4] The development of sound joints between dissimilar materials is a very important consideration for many emerging applications, including ship building, aerospace, transportation, power generation, as well as the chemical, nuclear, and electronics industries [5]. However, the joining of dissimilar materials by conventional fusion welding is difficult because of the poor weldability arising from the different chemical, mechanical, and thermal properties of welded materials and the formation of hard and brittle intermetallic compounds (IMCs) on a large scale at the weld interface. The absence of melting in friction stir welding (FSW) provides a strong tendency to produce reliable dissimilar joints. Amancio-Filho et al.[6] determined the tensile strength of dissimilar friction stir welded AA2024-T351 and AA6056-T4 as 56 % of the AA2024-T351 and 90 % of the AA6056-T4. It is reported that the poor tensile strength observed in these joints is due to the thermal softening of the base metals, and the poor ductility observed in these joints is due to the stress concentration caused by the large difference in strength between the base metals leading to confined plasticity and failure. Cavaliere et al.[Š4Ć] investigated the tensile behaviour of dissimilar friction stir welded joints of the aluminium alloys 2024-T3 and 7075-T6 and reported that both the ultimate strength and the elongation of the dissimilar joints are lower than the base metals 2024-T3 and 7075-T6. From the above literature review we can conclude that very little research work has been carried out on the dissimilar FS welding of aluminium alloys and that the dissimilar friction stir welding of AA6351 and AA5083, which are widely used in aerospace, ship building, and other fabrication industries,[7] were not investigated. Hence, the present research work focuses

Table 1: Chemical composition of AA6351-T6
Tabela 1: Kemična sestava zlitine AA6351-T6

Name of the Element	Si	Zn	Mg	Mn	Fe	Cu	Ti	Sn	Ni	Al
Masss fractions, *w*/% (AA6351)	0.907	0.89	0.586	0.65	0.355	0.086	0.015	0.003	0.002	Balance

Table 2: Chemical composition of AA5083-H111
Tabela 2: Kemična sestava zlitine AA5083-H111

Element	Si	Zn	Mg	Mn	Fe	Cu	Ti	Al
Mass fracions, *w*/% (AA5083-H111)	0.045	0.04	4.76	0.56	0.14	0.02	0.054	Balance

on the tensile behaviour of dissimilar friction stir welded joints of the aluminium alloys AA6351 and AA5083.

2 EXPERIMENTAL PROCEDURE

2.1 Manufacturing of FSW tools

Five different tools made of High Carbon High Chromium steel (HCHCr) having different pin profiles of Straight Square (SS), Tapered Square (TS), Straight Hexagon (SH), Straight Octagon (SO) and Tapered Octagon (TO) without draft were used to weld the FSW joints. Each tool had a shoulder of diameter 18 mm, a pin diameter of 6 mm and a pin length of 5.6 mm. The shoulder–workpiece interference surface had 3 concentric circular equally spaced slots of 2 mm depth on all the tools. The FSW tools were manufactured using a CNC turning center and a wire cut EDM (WEDM) machine to get an accurate profile. The tools were oil hardened. The manufactured tools are shown in **Figure 1**.

2.2 Frictions stir welding of dissimilar aluminium alloys

The aluminium alloys AA6351-T6 and AA5083-H111 were selected for the dissimilar friction stir welding process. The chemical compositions of the materials AA6351-T6 and AA5083-H111 are presented in **Tables 1 and 2** and the mechanical properties of the materials are presented in **Table 3**. Test plates of size 100 mm × 50 mm × 6 mm were prepared from rolled sheets.

The experimental set up consists of a special-purpose machine shown in **Figure 2** with arrangements designed for the friction stir welding. The plate AA 6351-T6 was fixed with the advancing side and the AA5083 H-111 was fixed with the retreating side of the machine. The vertical tool head can be moved along the vertical guide ways (*Z*-axis). The horizontal table can be moved along the *X*- and *Y*-axes and consists of mechanical fixtures to hold the workpieces rigidly. The machine can be operated over a wide range of tool rotational speeds, welding speeds and tool axial forces. Five different tool-pin profiles were used to produce the joints. Using each tool, three joints at three different welding speed levels and in

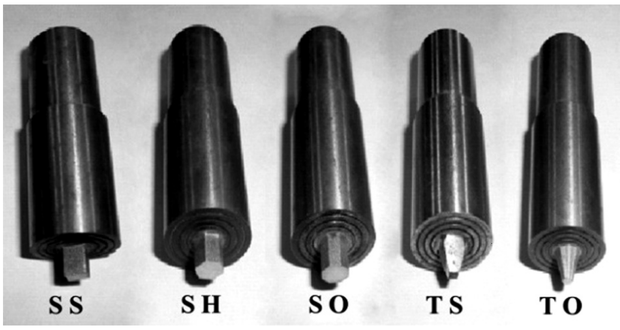

Figure 1: Manufactured tool for FSW (Straight Square (SS), Straight Hexagon (SH), Straight Octagon (SO), Tapered Square (TS), and Tapered Octagon (TO)
Slika 1: Trni za pomično torno varjenje: raven kvadrat (SS), koničen kvadrat (TS), raven šestokokotnik (SH), raven osmokotnik (SO) in koničen osmokotnik (TO)

Figure 2: Experimental setup
Slika 2: Eksperimentalna naprava

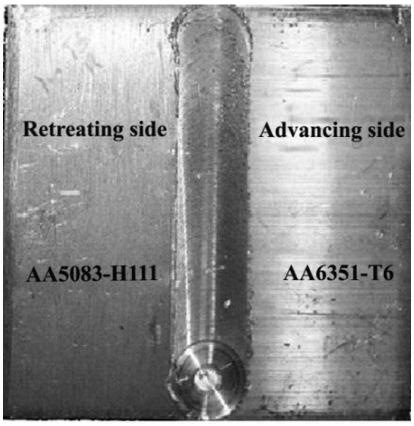

Figure 3: FS Welded sample (950 r/min, 1 t, 63 mm/min straight square pin profile)
Slika 3: Zvarjeni vzorec (950 r/min, 1 t, 63 mm/min, raven kvadraten profil)

Table 3: Mechanical properties of the AA6351 and AA5083-H111
Tabela 3: Mehanske lastnosti zlitin AA6351-T6 in AA5083-H111

Base Material	Tensile Strength (MPa)	Yield Strength (MPa)	Percentage of elongation
AA6351	310	285	14
AA5083-H111	308	273	23

Table 4: Welding process parameters
Tabela 4: Parametri procesa varjenja

Process parameter	Values
Tool rotational speed, r/min	950
Welding speed, mm/min	50,63,75
Axial force, t	1

total 15 joints (5 × 3) were produced in this study. The welding parameters are presented in **Table 4**. The joints were visually inspected for exterior weld defects and they were found to be free from any external defects. A sample of a friction stir welded plate is shown in **Figure 3**. The tensile test specimens were prepared according to the ASTM E8 standard and the transverse tensile properties of the FS welded joints were evaluated using a computerized (Universal Testing Machine) UTM. For each welded plate, three specimens were prepared and tested. The fracture occurred either on the retreating side or the advancing side of the weld. **Figure 4** shows the fractured tensile specimen.

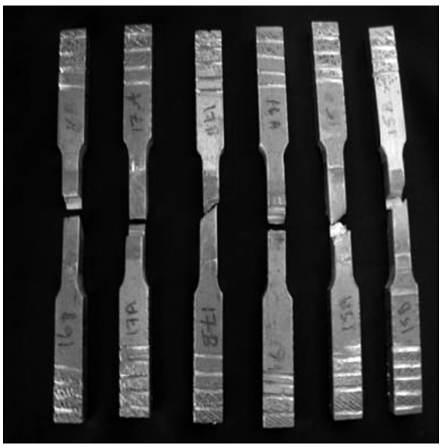

Figure 4: Tested specimen for tensile strength
Slika 4: Pretrgani natezni preizkušanci

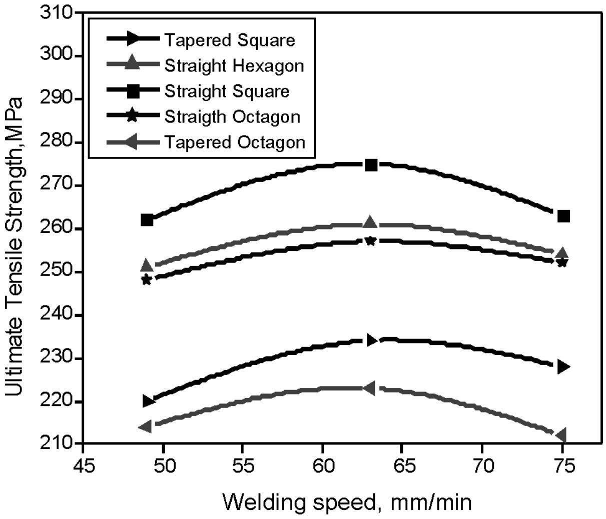

Figure 5: Effect of welding speed and pin profile
Slika 5: Vpliv hitrosti varjenja in profila trna

3 RESULTS

The effects of welding speed for various tool pin profiles are shown in **Figure 5**. At the lowest (50 mm/min) and the highest welding speeds (75 mm/min) a lower tensile strength was observed. This trend was common in all the joints, irrespective of the tool pin profile. The joint produced by the straight square pin profiled tool exhibits a high tensile strength when compared to the other joints. The joint produced by the tapered octagon pin profiled tool had the lowest tensile strength. The tensile strength of the joints welded using the straight hexagon and the straight octagon pin profiled tools did not differ significantly.

4 DISCUSSION

The increase in welding speed leads to an increase in the tensile strength up to a maximum value, while a further increase in the welding speed results in a decrease of the tensile strength of the FS welded joints. This is due to the increased frictional heat and insufficient frictional heat generated, respectively. [8] In general, FSW at higher welding speeds results in a short exposure time in the weld area with insufficient heat and a poor plastic flow of the metal and causes some void-like defects in the joints. The reduced plasticity and rates of diffusion in the material may have resulted in a weak interface. Higher welding speeds are associated with low heat inputs, which result in faster cooling rates of the welded joint. This can significantly reduce the extent of the metallurgical transformations taking place during welding and the local strength of the individual regions across the weld zone. [9] The pin profile plays a crucial role in the material flow and in turn regulates the welding speed of the FSW process. The relationship between the static volume and the dynamic volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool [10]. This ratio is equal to 1.56 for the straight square, 1.21 for the straight hexagon, 1.11 for the straight octagon, 2.04 for the tapered octagon and 3.51 for the tapered square pin profiles. In addition, these pin profiles produce a pulsating stirring action in the flowing material due to the flat faces. The square pin profile produces 63 pulses per second, the hexagon pin profile produces 95 pulses per second and the octagon pin profile produces 126 pulses per second, when the tool rotates at a speed of 950 r/min. There is not much pulsating action in the case of the octagonal and hexagonal pin profiled tool because it almost resembles a straight cylindrical pin profiled tool at this high rpm. In the tapered pin profiled tools, the same principle affects the material flow. Since the tapered square and tapered octagon pin profile sweeps less material when compared to that of the straight square pin tool, this joint exhibit less tensile properties.

5 CONCLUSION

Among the fifteen joints produced in this investigation, the joints produced using the straight square pin profiled tool at a welding speed of 63 mm/min showed the best tensile properties.

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