Comparison between microstructure characteristics and joint performance of 5086-H32 aluminium alloy welded by MIG, TIG and friction stir welding processes

E. Taban[1], E. Kaluc[1,2]*

[1] *Department of Mechanical Engineering, Engineering Faculty, Kocaeli University, Veziroglu Campus, 41200 Kocaeli, Turkey*
[2] *Welding Technology Research Center, Kocaeli University, Veziroglu Campus, 41200 Kocaeli, Turkey*

Received 29 August 2006, received in revised form 11 July 2007, accepted 13 August 2007

Abstract

In this study, conventional fusion welding processes: MIG, TIG and solid state process friction stir welding (FSW) were applied to 6.45 mm thick plates of 5086-H32 aluminium alloy. The weldments were evaluated by performing microstructural examinations including light optical microscope (LOM) and transmission electron microscope (TEM) and EDX analysis as well as hardness measurements. Mechanical testing has been done by means of tensile and bend tests. Fracture surfaces were examined by LOM and scanning electron microscope (SEM). Depending on the properties obtained, it has been determined that double pass friction stir welded joints of 5086-H32 aluminium alloy have superior properties than that of MIG and TIG welded joints.

Key words: 5086-H32 aluminium alloy, friction stir welding, MIG, TIG, microstructure, SEM, TEM

1. Introduction

Among aluminium alloys, 5086-H32 (AlMg4), commonly used in defence, shipbuilding, automotive, railway, aviation and aerospace industries, is a representative non-age-hardenable Al-Mg alloy that possesses an attractive combination of properties such as light weight, moderate high strength, good corrosion resistance, workability, proven weldability, good electrical and thermal conductivity [1–6].

For the joining of aluminium alloys, fusion welding processes have commonly been used in several industrial applications. A solid state process-friction stir welding, (FSW) invented and patented at The Welding Institute (TWI) of UK in 1991, is considered to be the most significant development in metal joining in a decade. This relatively new welding process has initially and particularly been applied for welding the high strength aluminium alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW of aluminium alloys has been used in the applications of aircraft, shipbuilding, automotive, railway, defence industries and attracted extensive research interest due to the potential engineering importance and problems such as reduced strength of the joints, distortions, residual stresses, gas porosities, metallurgical precipitations in the weld metal and HAZ, lack of fusion, high coefficient of thermal expansion, solidification shrinkage, high solubility of hydrogen and other gases associated with conventional welding [2–10].

The rapid development of FSW in aluminium alloys and its successful implementation into commercial applications has motivated its application to more non-ferrous materials and other metals [2, 9].

In FSW, as a basis, a non-consumable tool with a special designed pin and a shoulder is plunged into the abutting edges of the plates to be joined to a preset depth and moved along the weld joint. Heat is generated through the frictional contact between the rotating tool shoulder, abutting material surface and plastic deformation of workpiece [2, 5, 6, 9, 11–14].

*Corresponding author: tel.: +90 (262) 335 11 48 (1147 ext.); fax: +90 (262) 335 28 80; e-mail address: ekaluc@kou.edu.tr

Table 1. Chemical composition and mechanical properties of base metal

Chemical composition (wt.%)										
Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	V	Ti	Al
0.16	0.28	0.09	0.37	4.3	0.07	0.01	0.08	0.02	0.02	Bal.

Mechanical properties		
$R_{\mathrm{p}}0.2$ (MPa)	R_{m} (MPa)	Elongation (%)
240	331	15.2

In the literature, friction stir weldability of 5083 aluminium alloy has been investigated by several researchers [8, 14–23]. However, a study about the friction stir weldability of 5086-H32 alloy has not been found up to now. It is not only important to show the feasibility of FSW, but also to delineate its advantages and/or disadvantages over other techniques [9]. So, the objective of this investigation is to determine and compare the microstructural and mechanical properties of double-sided friction stir (FS) welds and conventional MIG and TIG welds of 6.45 mm thick 5086-H32 aluminium alloy. The microstructural investigation of the weld zones includes light optical microscope (LOM) and transmission electron microscope (TEM) examinations, EDX analysis as well as hardness measurements with 200 g load. Mechanical testing, tensile and bend tests were applied and in addition, fracture surfaces of the joints were studied and discussed with macrographs and SEM images.

2. Material and experimental procedures

In this paper, a non-heat treatable 5086-H32 Al-Mg alloy which is mainly used in the construction of tactical military vehicles and shipbuilding has been used. In Table 1, the chemical composition and the mechanical properties of the base metal have been demonstrated.

Welding processes that have been applied to the base metal are: MIG and TIG as conventional fusion welding processes and friction stir welding as solid state welding process. Butt joints of double sided welds were obtained.

MIG and TIG welds were produced semi-automatically in industrial conditions, with an ER 5356 (AlMg5Cr (A)) wire of 1.6 mm diameter in combination with 99.999 % Argon shield gas. Arc voltage and welding current varied respectively between 24 V and 26 V and between 180 A and 200 A. I grooves were cleaned with acetone and stainless steel brush prior to welding. AISI 4340 (0.40 % C, 0.70 % Mn, 0.30 % Si, 0.80 % Cr, 1.80 % Ni, 0.25 % Mo) tool was used for friction stir welding of the plates. M5 threaded tool had a shoulder diameter of 20 mm and 3.6 mm height standard pin. The welding tool was rotated in anti-clock direction with 2° tool tilting from the plate normal. 1600 rpm and 125 mm min^{-1} tool rotational and translation speeds were used, respectively.

Visual inspection of the welds was made with reference to ANSI/AWS B.1.11. Weld reinforcement and spatter dimensions were measured. All welded plates were subjected to distortion measurements.

As metallographic examination, the cross sections of the welded joints were prepared, polished and etched with modified Keller's reagent for about 30 s, visualized as macro- and micrographs using LOM. TEM investigation has also been applied to the thermo-mechanical affected zones of friction stir welds with 30 000× magnification. EDX analysis was carried out at the BM, TMAZ and WM at the friction stir welded samples. Microhardness measurements were carried out as line analysis, under 200 g test load at 2 mm depth from the face and root side of each cross section of the welds.

For mechanical testing, tranverse tensile and bend test specimens were prepared from the welded plates with reference to EN 895 and EN 910 standards, respectively. Weld reinforcement of the specimens was ground off. The tests were carried out using a servohydraulic test machine at room temperature.

To determine the fracture mode of welded joints, fracture surfaces of the specimens were examined using light microscope and scanning electron microscope (SEM).

3. Results and discussion

After the visual inspection of the plates, MIG and TIG welded joints were determined to be acceptable as no surface cracks and discontinuities were detected. Investigations have shown that the distortion rates of fusion welded plates, measured as 7.7 mm and 6.65 mm respectively for MIG and TIG welded plates, were higher than FSW joints, with 1.1 mm distortion rate. The results were within the acceptable limits. Due to the high heat input, the largest

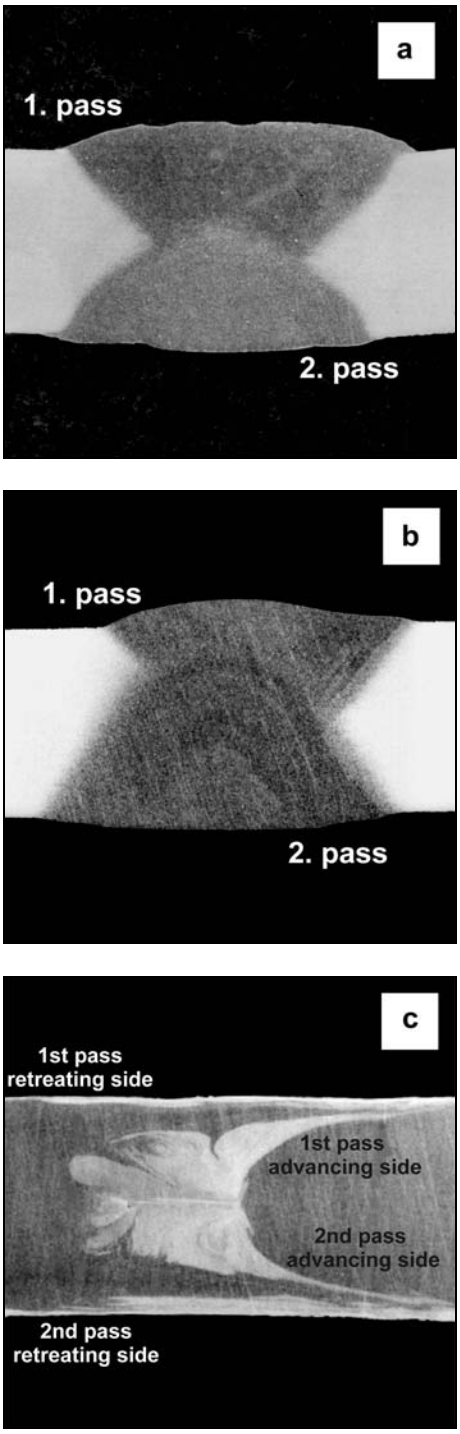

Fig. 1. Macro photos of specimens: (a) MIG welded, (b) TIG welded, (c) FS welded.

amount of distortion was determined on the MIG welded plate.

The microstructural investigation was carried out on the metallographic specimens of the joints using LOM, adapted with image analyses system. Macrographs of MIG, TIG and friction stir welded 5086-H32 specimens are illustrated in Fig. 1. Double pass weld beads can clearly be seen. Figure 1c demonstrates the friction stir welded sample with an interesting mixture of the material which depends on the welding parameters.

Micrographs of fusion and friction stir welded samples are illustrated in Fig. 2. In fusion welded cross sections, depending on the fusion of the aluminium alloy and high temperatures experienced by adjacent material, a fairly wide heat affected zone (HAZ) has been observed. As the same filler metal has been used for the MIG and TIG welding, similar microstructural morphologies have been observed, however some porosity has been determined in the weld metal (WM) of MIG welded sample. Based on the microstructural characterization, three distinct zones have been observed in friction stir welded samples. The nugget zone with onion ring structure and thermo-mechanical affected zone (TMAZ) that experiences both temperature and deformation during the process and HAZ, have been identified. An onion ring structure can be observed in the nugget zone whose recrystallized fine grain structure is generated as a result of plastic deformation and frictional heating. The nugget with onion rings and with a structure like pan-cake, the transition between the nugget and TMAZ, can be observed at the friction stir welded 5086-H32 alloy as shown in Figs. 2e and 2f.

Thin foil specimens for transmission electron microscopy (TEM) have been obtained from the base metal, thermo-mechanical heat affected zone (TMAZ) and the weld nugget of friction stir welded specimen. Microstructural examination has been carried out in a JEOL 3010 TEM operated at 300 kV. Dislocations and precipitations have been observed in TMAZ of FS welded specimen as shown in Fig. 3. TMAZ had higher dislocation density than the base material. In the TEM analysis of TMAZ, there has been deviation of the electrons as it means that the particles are ferromagnetic. Depending on the data obtained with EDX analysis of TMAZ, see Fig. 3d, these particles could be Al_6(Mg, Fe) particles.

For the hardness distribution in the weld zones, the solid solution hardened Al alloys have shown very different behaviour than the precipitation hardening alloys as reported by Mishra and Ma [9] and Lee et al. [24]. In the papers, for precipitation hardening alloys, it is explained that a softened region was formed in the weld zone because the precipitates disappeared or coarsened by the welding heat. Especially, such a softening was caused by dissolution and growth of strengthening precipitates (Mg_2Si, $MgZn_2$) during the thermal cycle of the welding. However, for the solid solution hardened alloys, generally a roughly homogeneous was determined as hardness profile depending on the dislocation density and strain hardening mechanism of the alloys.

Figure 4a shows the hardness graph of the wel-

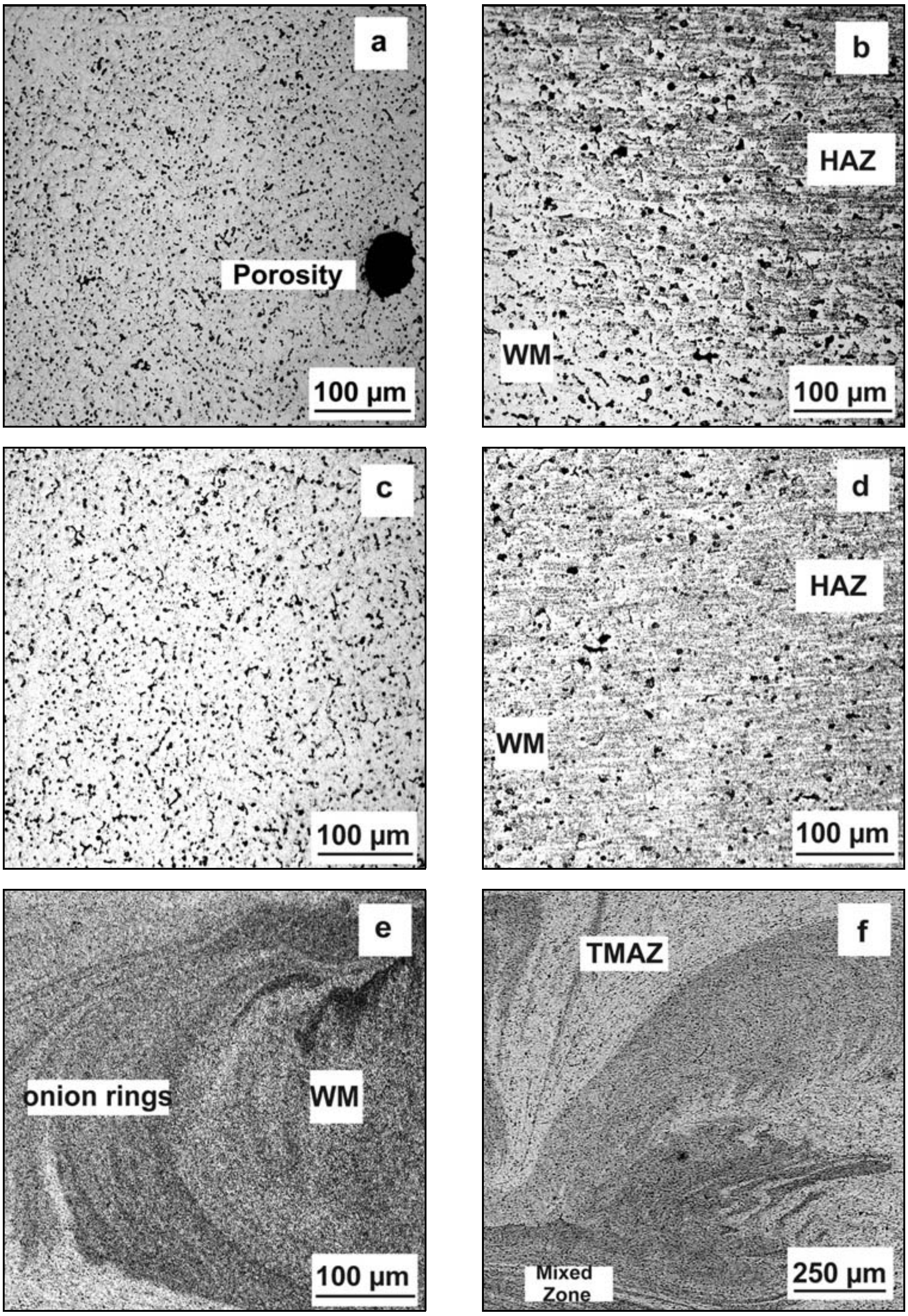

Fig. 2. Micrographs of the weld zones: (a) MIG weld metal (WM), (b) MIG WM + HAZ, (c) TIG WM, (d) TIG welded WM + HAZ, (e) FS WM, (f) FS WM + TMAZ.

ded joints. The hardness profile of friction stir welded 5086-H32 sample has been determined almost homogeneous similar to the reported graphs in the literature for the 5083 alloy. It has been explained by Lee et al. [24], Svensson et al. [25] and Sato et al. [26–28], that this situation was mainly governed by not only dislocation density, but also the distribution and size of the small Al_6(Mn, Fe) particles.

Figure 4b shows the mean values of the tensile properties of MIG, TIG and friction stir welded joints. Examination of the tensile test results of the welded joints has demonstrated that the average joint efficiency values of the welded joints are 82 %, 76 % and 85 % of the base material, respectively. The hardness plots confirm the order of the tensile strength values of the welded joints. Fracture of the welds occurred in

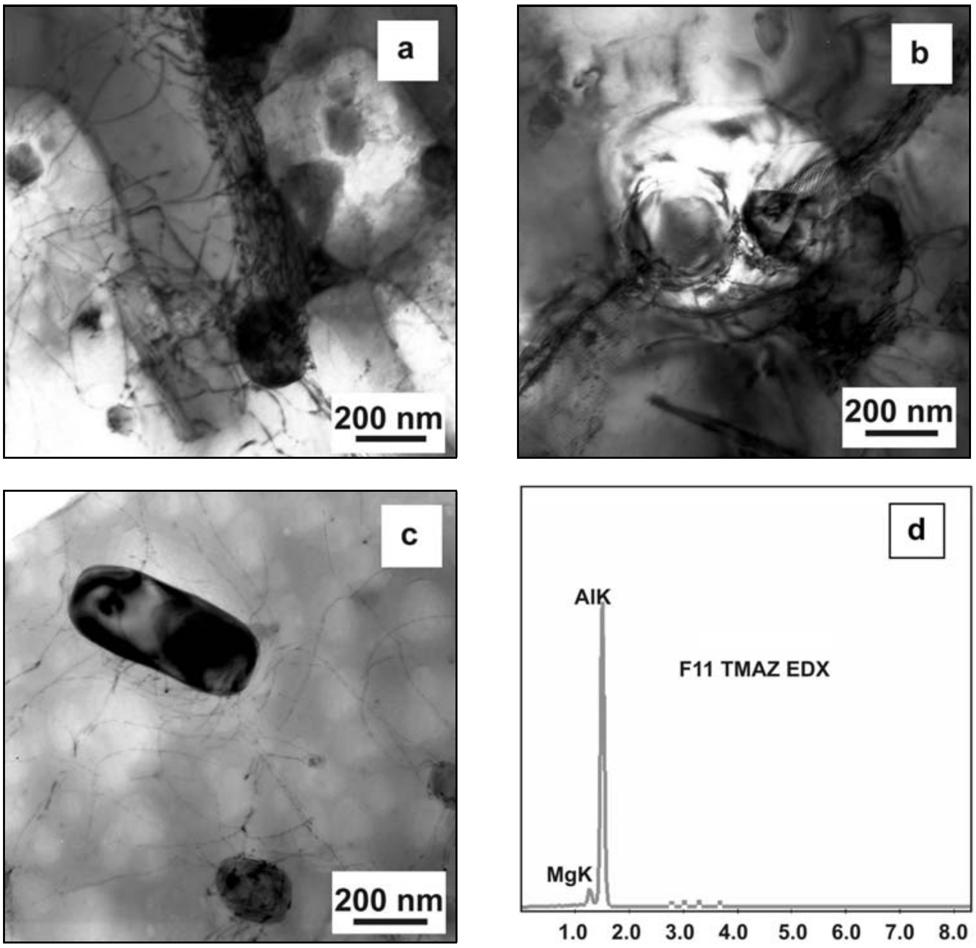

Fig. 3. TEM photos of TMAZ of the FS welded specimens: (a) and (b) with dislocations, (c) with precipitations, (d) EDX analysis.

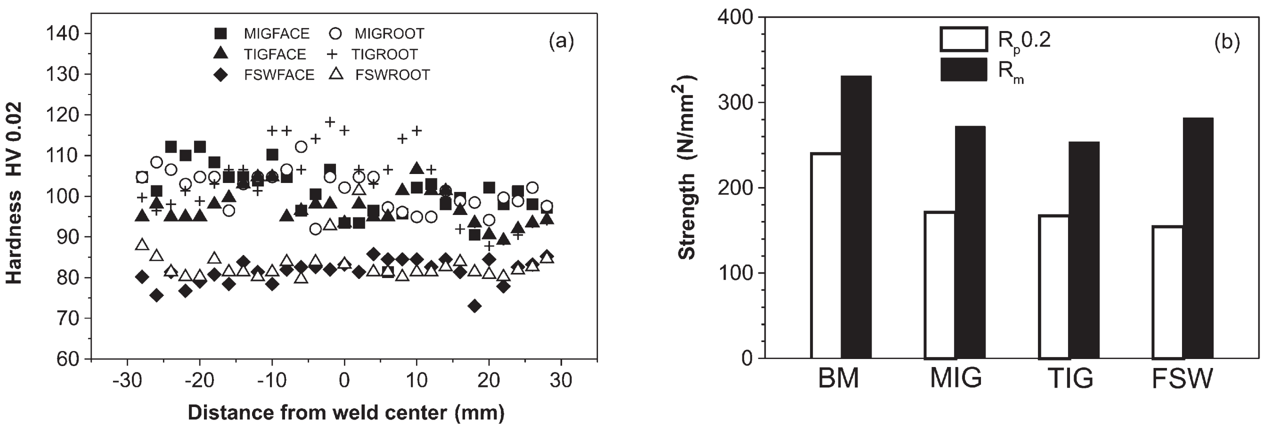

Fig. 4. (a) First and second pass hardness distributions of MIG, TIG and FS welded joints, respectively, (b) comparison of mean the base metal strength values with welded joints.

the weld metal (WM) for fusion welded and thermomechanically affected zone (TMAZ) advancing side for the friction stir welded joints, respectively. The strength increasing effect of strain hardened 5086-H32 aluminium alloy was eliminated by the high heat input of fusion welding and porosities in weld metal are the reason of this situation.

Porosities in the weld metals of MIG and TIG welded specimens can be observed in Figs. 5a–d illustrating the macrographs and SEM photographs

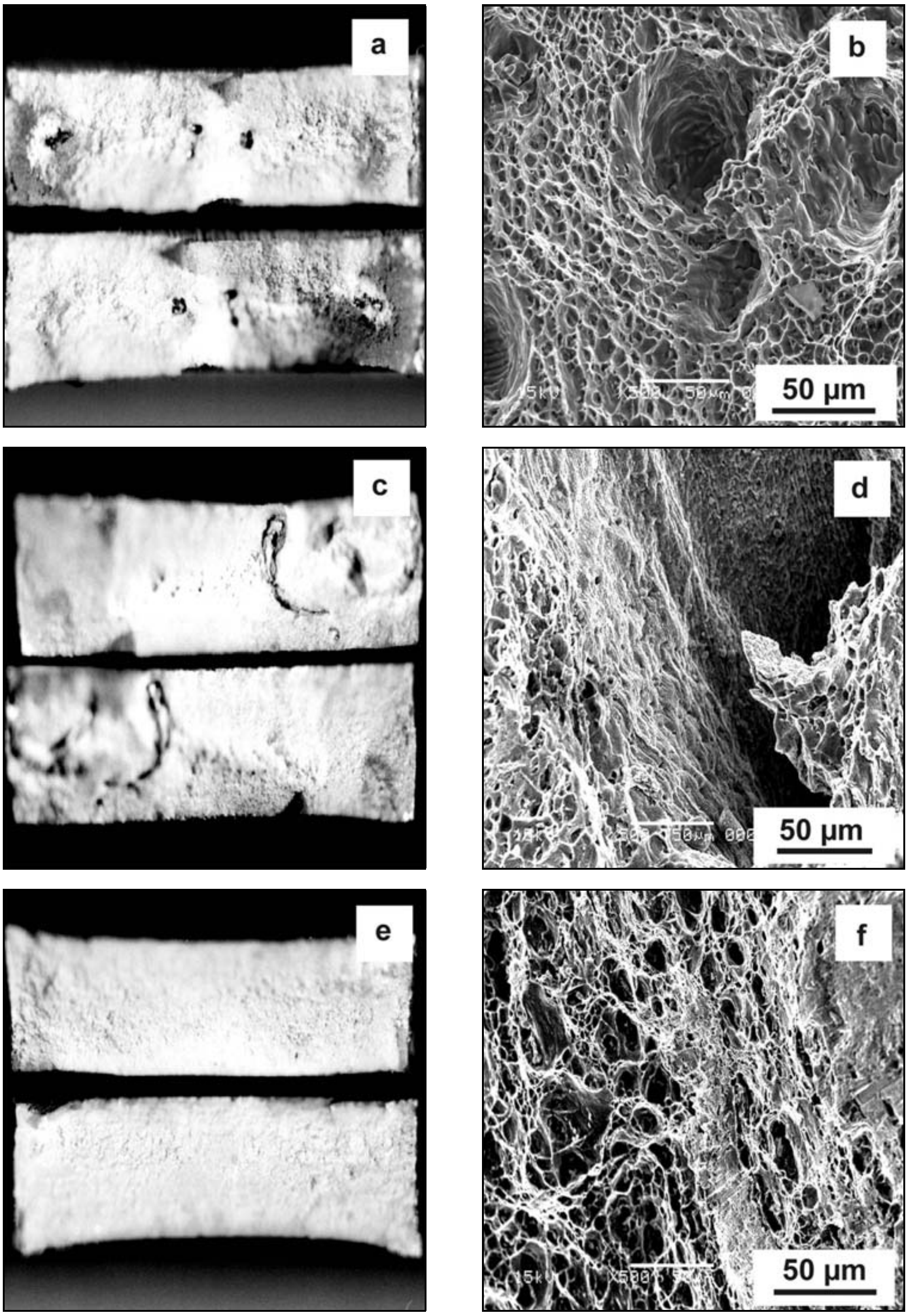

Fig. 5. Light macrographs and SEM images of the fracture surfaces: (a), (c) and (e) light macrographs, (b), (d) and (f) SEM photos of MIG, TIG and FS welded joints, respectively.

of fracture surfaces. Figure 5b is an enlarged SEM photograph showing a dimple pattern that indicates ductile fracture and the porosity in this matrix occurred. Figure 5d also contains the photograph of dimple patterns and some defects which caused fracture to initiate. Figures 5e and 5f exhibits the ductile fracture phenomena of FS welded specimens. Tensile testing of these joints showed that cracking tended to occur initially at the upper region of the joint and propagated towards the bottom region [29].

In the face and root bend test results of the welded specimens, although MIG and TIG welded specimens show some cracks, no crack was observed in friction stir welded specimens, see Table 2. Mechanical testing by means of tensile and bend tests has proved some

Table 2. Bend test results of the MIG, TIG and FS welded joints [29]

Welding process	Test type	Specimen code	Test result
MIG	Face bend	M86F1 M86F2	No crack No crack
	Root bend	M86R1 M86R2	Harmless crack No crack
TIG	Face bend	T86F1 T86F2	Harmless crack No crack
	Root bend	T86R1 T86R2	Harmless crack No crack
FSW	Face bend	F86F1 F86F2	No crack No crack
	Root bend	F86R1 F86R2	No crack No crack

more advantages of the friction stir welding process compared to fusion welding processes.

4. Conclusions

The conventional MIG and TIG welding processes and innovative friction stir welding (FSW) processes were successfully applied to join 5086-H32 aluminium alloy from double sides as it can be called as double-pass. The microstructural properties and hardness distributions, mechanical properties, examining of fracture surfaces of the joints have been studied in the present work. Following conclusions can be drawn:

The microstructure of double stir zones was mainly composed of onion ring structures in the nugget zones with fine and equiaxed grains, and double TMAZ were observed because of welding from double sides that improves the mechanical properties. The hardness profile was found roughly homogeneous similar to the examples in the literature. TEM study has revealed that TMAZ has higher dislocation density and particles as confirmed with EDX analysis affecting also the hardness distribution.

The present study has demonstrated that the tensile properties of FSW joints were more satisfactory than fusion welded joints. All fracture of FS welded specimens were occurred in TMAZ. Bend tests of welded plates have shown that FS welded specimens do not include any defect like fusion welded specimens. LOM and SEM examinations of the fracture surfaces exhibited porosities in MIG and TIG welds that have caused strength values to decrease; however FS welds do not include weld defects.

Acknowledgements

The authors would like to acknowledge FNSS Defence Industry Company for the cooperation, contribution and technical support. And so the cooperation of TWI during the FSW project with FNSS is also acknowledged. Financial support of Kocaeli University Research Fund in scope of research project (Project No: 2004/51) is appreciated. In addition many thanks to Prof. Dr. S. Karagoz and his team for SEM and to Dr. S. Akturk for TEM photographs. Acknowledgements to all colleagues at the Research Center of the Belgian Welding Institute for additional microstructural investigation, SEM and EDX analysis.

References

[1] ZHOU, C.—YANG, X.—LUANET, G.: Scripta Materialia, *53*, 2005, p. 1187.
[2] MATHERS, G.: The Welding of Aluminium and Its Alloys. Cambridge, Woodhead Publishing Limited 2002.
[3] ANDERSON, T.: Welding Journal, *81*, 2002, p. 77.
[4] ANDERSON, T.: Welding Journal, *83*, 2004, p. 28.
[5] JOHNSEN, M. R.: Welding Journal, *78*, 1999, p. 35.
[6] KALLEE, S. W.—DA VENPORT, J.—NICHOLAS, E. D.: Welding Journal, *81*, 2002, p. 47.
[7] TABAN, E.—KALUC, E.:. Kovove Mater., *44*, 1, 2006, p. 25.
[8] KALUC, E.—TABAN, E.: DVS Annual Welding Conference, Schweissen und Schneiden, Essen, Germany 2005, p. 489.
[9] MISHRA, R. S.—MA, Z. Y.: Materials Science and Engineering R, *50*, 2005, p. 1.
[10] DAWES, C. J.—THOMAS, W. M.: Welding Journal, *75*, 1996, p. 41.
[11] CANTIN, G. M. D. et al.: Science and Technology of Welding and Joining, *10*, 2005, p. 268.

[12] DAWES, C. J.—THOMAS, W.: TWI Bulletin 6, Reprint 493/6/95, Cambridge 1995, p. 124.
[13] COLLIGAN, K. J.—KONKOL, P. J.—FISHER, J. J.—PICKENS, J. R.: Welding Journal, *82*, 2003, p. 34.
[14] THREADGILL, P.: TWI Bulletin, Reprint 513/2/97, Cambridge 1997.
[15] PEEL, M.—STEUWER, A.—FREUSS, M.—WITHERS, P. J.: Acta Materialia, *51*, 2003, p. 4791.
[16] JAMES, M. N.—HATTINGH, D. G.—BRADLEY, G. R.: International Journal of Fatigue, *25*, 2003, p. 1389.
[17] LARSSON, H.—KARLSSON, L.: Svetsaren, *2*, 2000, p. 6.
[18] LIU, H. J.—FUJII, H.—MAEDA, M.—NOGI, K.: Transactions of Nonferrous Metals Society of China, *13*, 2003, p. 14.
[19] DICKERSON, T. L.—PRZYDATEK, J.: International Journal of Fatigue, *25*, 2003, p. 1399.
[20] SHIGEMATSU, I.—KWON, Y. J.—SUZUKI, K.—IMAI, T.—SAITO, N.: Journal of Materials Science Letters, *22*, 2003, p. 353.
[21] VAZE, S. P.—XU, J.—RITTER, R. J.—COLLIGAN, K. J.—FISHER, J. J.—PICKENS, J. R.: Materials Science Forum, *426–432*, 2003, p. 2979.
[22] REYNOLDS, A. P.—LOCKWOOD, W. D.—SEIDAL, T. U.: Materials Science Forum, *331–337*, 2000, p. 1719.
[23] MCLEAN, A. A.—POWELL, G. L. F.—BROWN, I. H.—LINTON, V. M.: Science and Technology of Welding and Joining, *8*, 2003, p. 462.
[24] LEE, W. B.—YEON, Y. M.—JUNG, S. B.: Materials and Engineering, *A355*, 2003, p. 154.
[25] SVENSSON, L. E.—KARLSSON, L.—LARSSON, H.—KARLSSON, B.—FAZZINI, M.—KARLSSON, J.: Science and Technology of Welding and Joining, *5*, 2000, p. 285.
[26] SATO, Y. S.—KOKOWA, H.—ENOMOTO, M.—JORGAN, S.: Metall. Mater. Trans., *A 30*, 1999, p. 2429.
[27] SATO, Y. S.—KOKOWA, H.—ENOMOTO, M.—JORGAN, S.—HASHIMOTO, J.: Metall. Mater. Trans., *A 30*, 1999, p. 3125.
[28] SATO, Y. S.—PARK, S. H. C.—KOKOWA, H.: Metall. Mater. Trans., *A 32*, 2001, p. 3033.
[29] TABAN, E.: Investigation on Mechanical and Microstructural Properties of TIG, MIG and FS Welded 5xxx Series Aluminium Alloys. [MSc Thesis]. Kocaeli University, Turkey 2004.