Journal
of Achievements in Materials
and Manufacturing Engineering

VOLUME 30
ISSUE 2
October
2008

Mechanical properties of friction stir butt-welded Al-5086 H32 plate

G. Çam [a],*, S. Güçlüer [b], A. Çakan [c], H.T. Serindağ [a]
[a] Mustafa Kemal University, Faculty of Engineering and Architecture, 31040 Antakya, Turkey
[b] General Directorate of Highways of Turkey, Ankara, Turkey
[c] Abant Izzet Baysal University, Faculty of Engineering and Architecture, 14280 Bolu, Turkey
* Corresponding author: E-mail address: gurelcam@gmail.com

Received 30.06.2008; published in revised form 01.10.2008

Properties

ABSTRACT

Purpose: The purpose of the paper is to study Al-5086 H32 plates with a thickness of 3 mm friction stir butt-welded using different welding speeds at a tool rotational speed of 1600 rpm.
Design/methodology/approach: The effect of welding speed on the weld performance of the joints was investigated by conducting optical microscopy, microhardness measurements and mechanical tests (i.e. tensile and bend tests). The effect of heat input during friction stir welding on the microstructure, and thus mechanical properties, of cold-rolled Al- 5086 plates was also determined.
Findings: The experimental results indicated that the maximum tensile strength of the joints, which is about 75% that of the base plate, was obtained with a traverse speed of 200 mm/min at the tool rotational speed used, e.g. 1600 rpm, and the maximum bending angle of the joints can reach 180º. The maximum ductility performance of the joints was, on the other hand, relatively low, e.g. about 20%. These results are not unexpected due to the loss of the cold-work strengthening in the weld region as a result of the heat input during welding, and thus the confined plasticity within the stirred zone owing to strength undermatching. Higher joint performances can also be achieved by increasing the penetration depth of the stirring probe in butt-friction stir welding of Al-5086 H32 plates.
Research limitations/implications: The results suggest that both strength and ductility performances can be increased by optimizing the tool penetration depth.
Originality/value: Examination of mechanical properties of friction stir butt-welded Al-5086 H32 plate.
Keywords: Friction stir welding; Al-alloys; Joint performance; Strength undermatching

1. Introduction

Friction stir welding (FSW) is a new solid-state welding method developed by The Welding Institute (TWI) in 1991 [1]. The weld is formed by the excessive deformation of the material at temperatures below its melting point, thus the method is a solid state joining technique. There is no melting of the material, so FSW has several advantages over the commonly used fusion welding techniques [2-10]. For example, there are no porosity or cracking in the weld region, there is no significant distortion of the workpieces (particularly in thin plates), and there is no need for filler materials, shielding gases and costly weld preparation during this joining process. FSW is considered to be the most remarkable and potentially useful welding technique for several materials, such as Al-alloys, Mg-alloys, brasses, Ti-alloys, and steels [1-16]. However, during FSW process using inappropriate welding parameters can cause defects in the joint and deteriorate the mechanical properties of the FSW joints [2, 3].

The technique has initially been widely investigated for mostly low melting materials, such as Al, Mg and Cu alloys. It has proven to be very useful, particularly in the joining of the difficult-to-fusion join high strength Al-alloys used in aerospace applications, such as highly alloyed 2XXX and 7XXX series aluminium alloys. The difficulty of making high-strength, fatigue and fracture resistant welds in these aluminium alloys has long inhibited the use of welding processes for joining aerospace structures. Instead, mechanical fastening (e.g. riveting) has been the usually preferred joining method except in production of pressure vessels for rocket propellant and oxidizer tanks. Many of the problems with welds in aerospace Al-alloys stem from the unfavourable distribution of brittle solidification products, cracking and porosity in the weld region. Encouraging results obtained in FSW of high-strength aerospace aluminium alloys, that are typically difficult-to-weld, have expanded the practical use of this technique.

Similarly, the welding of high carbon steels often includes the undesirable results of low ductility and high hardness, which has to be improved by relatively expensive pre- and post-weld heat treatments. The application of FSW to steels and other high temperature materials had originally been limited due to the absence of a suitable tool material, which is required to remain intact at temperatures higher than 1000°C. FSW has, however, been expected to be an effective way to join ferrous materials with poor fusion weldability owing to the fact that the process is a solid-state welding method. After this shortcoming was overcome through the development of suitable tools, investigations were conducted on the applicability of FSW for steels.

Early studies have shown that mild steel and other low to medium carbon ferrous alloys can successfully be friction stir welded [17-22] and grain refinement in the stir zone of the carbon steel, similar to Al alloys, is achieved. These encouraging results have stimulated the investigations on FSW of high carbon steels. Early reports show that joints with good mechanical properties can be achieved by grain refinement in the friction stir zone by controlling the temperature during FSW [23]. Thus, the application of this relatively new joining process has been expanded from low-to-medium melting point non-ferrous alloys to higher melting point difficult-to-fusion join ferrous alloys.

In this study, 3 mm thick Al-5086 H32 plates were friction stir welded using different welding speeds at a tool rotational speed of 1600 rpm. The effect of welding speed on the weld performance of Al-5086 alloy friction stir welded joints (i.e. loss of cold work hardening) was investigated by conducting optical microscopy, microhardness measurements and mechanical tests (i.e. tensile and bend tests). The effect of heat input during friction stir welding on the microstructure, and thus mechanical properties, of cold-rolled Al- 5086 plates was also determined.

2. Experimental procedure

In this study, 3 mm thick Al-5086 plates in H32 condition (i.e., a quarter cold-worked) were used for friction stir butt-welding trials. The chemical composition of the Al-alloy plate used in this study is given in Table 1. Table 2 shows the mechanical properties of the plate used. Friction stir welding of the plates was conducted using a vertical-spindle type milling machine [16].

A stirring tool made of a high speed steel (HSS) with a nominal composition of 1.27% C, 4% Cr, 3.6% Mo, 9.5% W, 10% Co and 3.2% V (material number being 1.3207) was employed in friction stir welding trials. The tool was slightly conical, the root diameter being 4 mm and the tip diameter being 3 mm. Its penetration depth was 2.8 mm. The reason for choosing a slightly conical tool is to determine whether it is possible to employ higher rotational and travel speeds in friction stir welding of Al-5086 plates by increasing the surface area of the tool, thus increasing the frictional heat. The tool used was a pin type with non-standard helical threads and its tip was rounded. A tool rotational speed of 1600 rpm was chosen for these trials. The plates were joined employing three different traverse speeds, namely 175, 200, and 225 mm/min.

The joint performance was determined by conducting optical microscopy, microhardness measurements and mechanical testing (e.g. tensile and bend tests). The metallography specimens extracted from the joints were mounted in polyester at room temperature to avoid the microstructural alterations which might take place during hot-mounting. The specimens were then grounded with silicon carbide papers of 240, 400, 800, 1000 and 1200 grades followed by polishing on a rotating wheel with 1 and 0.3 micron alumina suspension. All polished specimens were etched with a solution comprising 15 ml HNO_3 and 10 ml HF in distilled water for optical microscopy. A detailed microstructural observation was conducted for each welded plate using optical microscopy to determine the presence of any weld defect.

Furthermore, microhardness measurements were conducted on each welded plate to determine hardness variations across the stirred zones. Vickers microhardness measurement method was employed with a load of 100 grams (loading time being 5 seconds) for microhardness measurements. Furthermore, minimum three tensile specimens prepared according to EN 895 were tested for each condition to determine the mechanical performances of the joints obtained as explained in detail in an earlier publication [16]. The results were compared with those obtained from the base plate specimens. Moreover, two non-standard bending specimens (20 mm wide and 200 mm long) were also extracted from each welded plate [16]. Both specimens were bended up to 180°, one specimen with weld root being outside and the other with weld root inside, to determine whether cracking occurs or not in both bending conditions. Thus, the effect of welding speed at a given rotational speed on the mechanical performance was determined.

Table 1.
Nominal composition of the Al-5086 H32 plates used in this study

Element	Al	Mg	Mn	Cr	Cu	Fe	Si	Ti	Zn	others
wt %	93-96.3	3.5-4.5	0.2-0.7	0.005-0.25	max. 0.1	max. 0.5	max. 0.4	max. 0.15	max. 0.25	max. 0.15

Table 2.
Mechanical properties of the Al-5086 H32 plates used in this study

Hardness, HV	Tensile Strength, MPa	Proof Stress, MPa	Elongation, %	E, GPa
85	354	237	12	71

3. Results and discussions

3.1. Microstructure and hardness

Extensive microstructural observations were conducted to investigate the microstructural aspects of the joints produced. Figure 1 illustrates the cross-sections of some of the joints obtained. A very small amount of porosity was determined in the joints produced, except the one joined with a traverse speed of 175 mm/min which contained larger amounts of porosity in the weld zone, Fig. 1. This indicates that a traverse speed of 175 mm/min at the rotational speed used, i.e. 1600 rpm, was not convenient to achieve a sound stirred zone. As seen from Figure 1, there also seems to be kissing-bond type defects at the roots of the weld zones of the joints, indicating that the tool length was slightly shorter than needed or the depth of tool penetration was insufficient.

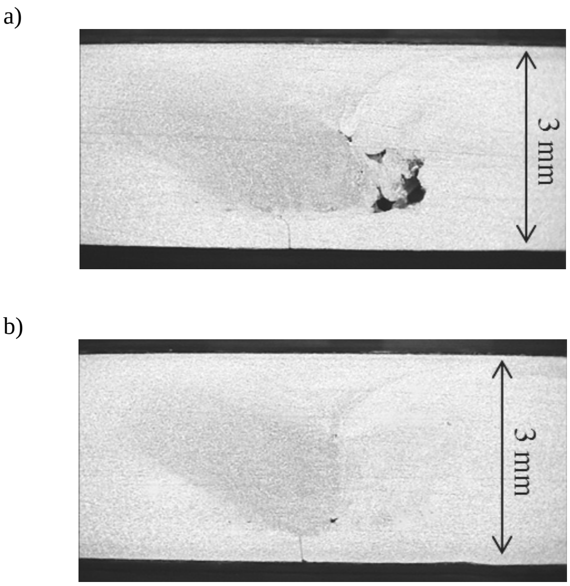

Fig. 1. Optical micrographs showing the cross-sections of the joints produced at different traverse speeds: a) 175 mm/min and b) 200 mm/min

Hardness measurements conducted across the stirred zones of all the joints produced exhibited a hardness decrease within the weld area. Figure 2 shows an example of the hardness profiles obtained from the joints across the stirred zone, which indicates a hardness decrease of about 15 HV within the stirred zone. This strength undermatching (i.e., loss of strength) is due to the fact that the softening of cold-worked material takes place as a result of the heat input during joining. Similarly, a loss of strength in the stirred zones of other friction stir-joined cold-worked Al-alloy plates (i.e., Al-5454 H32) was also reported by other researchers [2, 24].

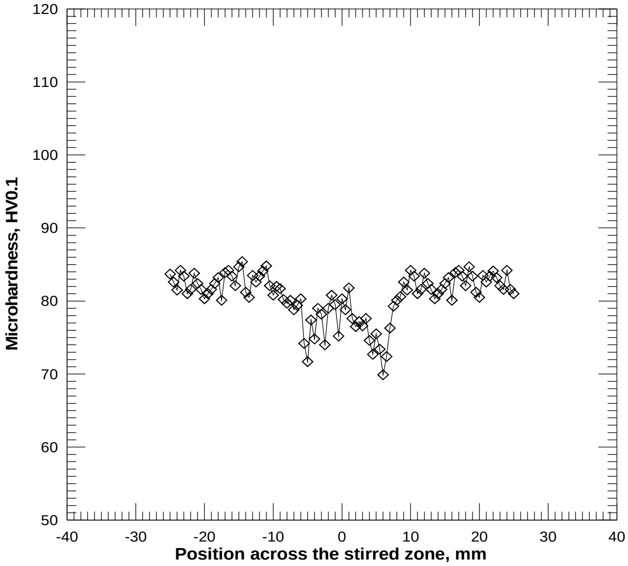

Fig. 2. Hardness profile across the stirred zone of the joint produced with a traverse speed of 200 mm/min (Note the loss of strength in the weld region)

3.2. Joint performance

Tensile test results of the specimens extracted from base plates and friction stir welded Al-5086 plates and the joint efficiency values obtained are summarized in Table 3. All the specimens extracted from the joints produced failed within the stirred zone. Microhardness measurements are in accordance with these results, as given in Fig. 2. This can be attributed to the loss of cold-work hardening within the stirred zone due to the heat input experienced by the plates during welding.

Figure 3 illustrates the comparison of the stress-strain curves of the specimens extracted from the base plates and the friction stir welded plate with a traverse speed of 200 mm/min, which exhibited best combination of mechanical properties among all the traverse speeds used. The highest strength and ductility performances obtained from the joint produced with a traverse speed of 200 mm/min at the tool rotational speed used (i.e. 1600 rpm) were 75% and 25%, respectively, as also seen from Fig. 4. The low ductility performance, i.e. 25%, is very common in Al-alloys welded joints (particularly cold-worked or precipitation hardened grades) due to the loss of strength within the weld region [4, 25-27].

Slightly lower strength performance values were reported for Al-5454 H32 plates (i.e., max. 72%), that were friction stir welded using much lower rotational and traverse speeds than those employed in this work. However, much higher ductility performances were obtained, i.e. >100%, for these welding conditions [2, 24]. This is not surprising since the lower the weld speed the higher the rate of softening within the stirred zone, thus higher ductility performance values can be obtained at the cost of lower strength performance. Furthermore, the lower ductility performance obtained in this work compared to those reported in

[24] might partially be due to the insufficient tool penetration, resulting in the formation of kissing-bond type defect at the root of the joint area. Thus, these results indicate that the joint performance values can further be improved by eliminating the kissing-bond type defects observed in the welds produced (Fig. 1) through optimizing the depth of tool plunging. Moreover, a high ductility performance (>100%), as reported in [24], is not a usual case for the joints with lower strength within the weld zone, due to the confined plasticity (i.e., increased constraint) [28-30].

Table 3.
Results of tensile tests of the specimens extracted from the base plate and welded plates

Specimen	Tensile Strength (MPa)	% Elongation	Strength Performance (%)*	Ductility Performance (%)**
Base plate	327; 346 354; 388 (Av.: 354)	12.5; 12.5 11.9; 11.7 (Av.: 12.2)	--	--
1600 rpm, 175 mm/min	183; 203 249; 290 (Av.: 231)	1.1; 1.3 2.0; 1.5 (Av.: 1.5)	52; 57 70; 82 (Av.: 65)	9; 11 16; 12 (Av.: 12)
1600 rpm, 200 mm/min	254; 261; 279 (Av.: 265)	2.5; 2.8; 3.8 (Av.: 3.0)	72; 74; 79 (Av.: 75)	20; 23; 31 (Av.: 25)
1600 rpm, 225 mm/min	244; 248 257; 289 (Av.: 260)	1.2; 1.2 1.2; 1.8 (Av.: 1.4)	69; 70 73; 82 (Av.: 74)	10; 10 10; 15 (Av.: 11)

*Strength performance=(TSweld/TSBM)x100;
**Ductility performance=(%elweld/%elBM)x100

The specimens extracted from the joint produced with a traverse speed of 225 mm/min also exhibited relatively high strength performance, i.e. 74%. However, the ductility performance of this joint was much lower, i.e. 11%, compared to that of the joint produced with a traverse speed of 200 mm/min. The joint produced with the lowest traverse speed, i.e. 175 mm/min, displayed the lowest performance values, Table 3.

The results of bending tests conducted are also in accordance with the tensile test results. No cracking was observed in the bend tests of the joints in both test conditions, i.e. with the weld root inside and outside, although the porosity was always present. The only exception to that was the specimen extracted from the joint produced with a traverse speed of 175 mm/min, which did crack in the bend test in the weld root outside condition. This is apparently due to the presence of significant porosity and kissing-bond type defect in the stirred zone of this joint. This is obvious because of the fact that the shielding of porosity takes place owing to the strength undermatching nature of the stirred zone (lower strength than that of the base plate).

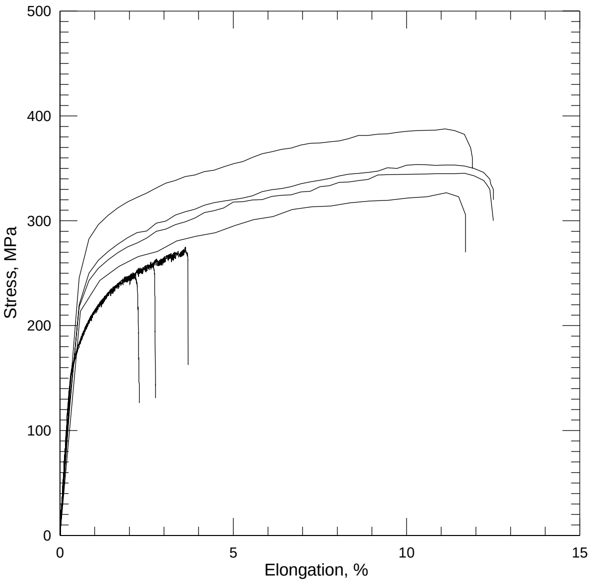

Fig. 3. Comparison of the stress-strain curves of the base plate (BM) specimens and the specimens extracted from the joint (FSW) produced with a traverse speed of 200 mm/min

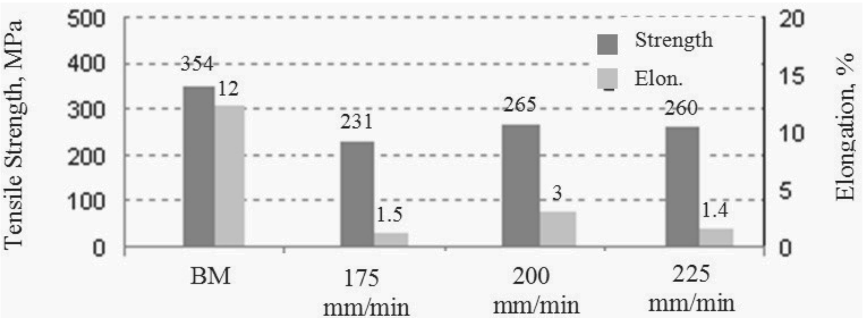

Fig. 4. Comparison of the mechanical properties of the base plate (BM) and the specimens extracted from the joints produced with different traverse speeds

4. Conclusions

The following conclusions have been drawn from the present study:

- Al-alloy Al-5086 H32 plates were successfully friction stir butt-joined using a slightly conical tool at a rotational speed of 1600 rpm.
- Formation of extensive porosity in the stirred zone was observed only in the joint produced with traverse speed of 175 mm/min, indicating that this travel speed is not sufficient to produce sound joints at the rotational speed used, i.e. 1600 rpm. The other joints contain only a small amount of porosity in the stirred zone. However, a kissing-bond type defect was observed in all the joints produced, indicating that the depth of tool penetration was not optimal.
- The best combination of strength and ductility performances (i.e., 75% and 25%, respectively) was obtained from the joint produced with a traverse speed of 200 mm/min at the tool rotational speed used, i.e. 1600 rpm.
- The reason for the lower strength performance, i.e. 75%, is the fact that the softening of cold-worked material takes place in the joint region as a result of the heat input during joining, which is usual in Al-alloys weldments, in conjunction with the presence of the kissing-bond type defect in the joint area.
- The relatively low ductility performance, on the other hand, can be attributed to a combination of kissing-bond type defect in the joint area and loss of strength within the stirred zone, resulting in confined plasticity. The results also suggest that both strength and ductility performances can further be increased by optimizing the tool penetration depth.

Acknowledgements

The authors would like to express their gratitude to the Scientific Research Projects Unit of Mustafa Kemal University, Hatay, Turkey, for partially financing this work (project number: 06 D 0202). We are also indebted to FNSS (Gölbaşı, Ankara, Turkey) for the supply of Al-5086 H32 plates used in this work. Thanks are also due to the companies, namely Ekmekçi Makine A.Ş., (Antakya, Turkey) and HAZ Metal A.Ş. (İskenderun, Turkey), for their contributions to the experimental work. We would also like to thank Dr. M. Kemal SANGÜN, Dr. Ekrem AKTOKLU, and Mr. Hidayet DUMAN from Mustafa Kemal University for their help in the experiments.

References

[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P.Temple-Smith, C.J. Dawes, International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978.8 and US Patent Application No. 5,460,317, December 1991.

[2] G. Çam, M. Koçak, Joining of advanced materials, Area 6: Materials science and engineering, Topic 6.36.4: Materials processing and manufacturing technologies, in: Encyclopedia of Life Support Systems (EOLSS), Eolss Publishers, Oxford, on line: http://www.eolss.net/.

[3] G. Çam, Recent developments in friction stir welding, Makina Tek. 120 (2007) 48-58 (in Turkish).

[4] A. Von Strombeck, G. Çam, J.F. Dos Santos, V. Ventzke, M. Koçak, A comparison between microstructure, properties, and toughness behavior of power beam and friction stir welds in al-alloys (keynote lecture), Proceedings of the TMS 2001 Annual Meeting "Aluminum Automotive and Joining Symposia" Aluminum 2001, New Orleans, 2001, 249-264.

[5] C.J. Dawes, W.M. Thomas, Friction stir process welds aluminum alloys. The process produces low-distortion, high-quality, low-cost welds on aluminum, Welding Journal 75 (1996) 41-45.

[6] C.G. Rhodes, M.W. Mahoney, W.H. Bingel, Effects of friction stir welding on microstructure of 7075 aluminium, Scripta Materialia 36 (1997) 69-75.

[7] M.W. Mahoney, C.G. Rhodes, Properties of friction-welded 7075 T651 aluminum, Metallurgical and Materials Transactions 29A (1998) 1955-1964.

[8] L.E. Murr, G. Liu, J.C. McClure, A TEM study of precipitation and related microstructures in friction-stir-welded 6061 aluminium, Journal of Materials Science 33 (1998) 1243-1251.

[9] O.V. Flores, C. Kennedy, L.E. Murr, D. Brown, S. Pappu, B.M. Nowak, J.C. McClure, Microstructural issues in a friction-stir-welded aluminum alloy, Scripta Materialia 38 (1998) 703-708.

[10] S.W. Kallee, J. Davenport, E.D. Nicholas, Railway manufacturers implement friction stir, Welding Journal 81/10 (2001) 47-50.

[11] D. Zhang, M. Suzuki, K. Murayama, Microstructural evolution of a heat-resistant magnesium alloy due to friction stir welding, Scripta Materialia 52 (2005) 899-903.

[12] H.S. Park, T. Kimura, T. Murakami, Y. Nagano, K. Nakata, M. Ushio, Microstructures and mechanical properties of friction stir welds of 60% Cu–40% Zn copper alloy, Materials Science Engineering A 371 (2004) 160-169.

[13] A.J. Ramirez, M.C. Juhas, Microstructural evolution in Ti-6Al-4V friction welds, Materials Science Forum 426 (2003) 2999-3004.

[14] R. Ueji, H. Fujii, L. Cui, A. Nishioka, K. Kunishige, K. Nogi, Friction stir welding of ultrafine grained plain low-carbon steel formed by the martensite process, Materials Science Engineering A 423 (2006) 324-330.

[15] Y.S. Sato, H. Yamanoi, H. Kokowa, T. Furuhara, Microstructural evolution of ultrahigh carbon steel during friction stir welding, Scripta Materialia 57 (2007) 557-560.

[16] G. Çam, H.T. Serindag, A. Çakan, S. Mistikoglu, H. Yavuz, Mat.-wiss. u. Werkstofftech. 39/6 (2008) 394-399.

[17] W.M. Thomas, P.L. Threadgill, E.D. Nicholas, Feasibility of friction stir welding steel, Science and Technology of Welding and Joining 4 (1999) 365-372.

[18] T.J. Lienert, W.L. Stellwag, B.B. Grimmett, R.W. Warke, Friction stir welding studies on mild steel, Welding Journal 82 (2003) 1-9.

[19] A.P. Reynolds, W. Tang, M. Posada, J. DeLoach, Friction stir welding of DH36 steel, Science and Technology of Welding and Joining 8 (2003) 455-460.

[20] H. Fujii, R. Ueji, Y. Takada, H. Kitahara, N. Tsuji, K. Nakata, K. Nogi, Friction stir welding of ultrafine grained interstitial free steels, Materials Transactions 47 (2006) 239-242.

[21] H. Fujii, L. Cui, M. Maeda, K. Nogi, Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys, Materials Science Engineering A 419 (2006) 25-31.

[22] H. Fujii, L. Cui, N. Tsuji, M. Maeda, K. Nakata, K. Nogi, Friction stir welding of carbon steels, Materials Science Engineering A 429 (2006) 50-57.

[23] L. Cui, H. Fujii, N. Tsuji, K. Nogi, Friction stir welding of a high carbon steel, Scripta Materialia 56 (2007) 637-640.

[24] A.P. Reynolds, Mechanical and corrosion performance of TGA and friction stir welded aluminum for tailor welded blanks: alloys 5454 and 6061, Proceedings of the 5th International Conference “Trends in Welding Research”, Pine Mountain, 1998, 563-567.

[25] G. Çam, M. Koçak, Microstructural and mechanical characterization of electron beam welded Al-alloy 7020, Journal of Materials Science 42/17 (2007) 7154-7161.

[26] G. Çam, V. Ventzke, J.F. dos Santos, M. Koçak, G. Jennequin, P. Gonthier-Maurin, M. Penasa, C. Rivezla, Characterization of laser and electron beam welded Al alloys, Practical Metallography 37/2 (2000) 59-89.

[27] G. Çam, V. Ventzke, J.F. dos Santos, M. Koçak, G. Jennequin, P. Gonthier-Maurin, Characterisation of electron beam welded aluminium alloys, Science and Technology of Welding and Joining 4/5 (1999) 317-323.

[28] M. Koçak, M. Pakdil, G. Çam, Fracture behaviour of diffusion bonded titanium alloys with strength mismatch, Science and Technology of Welding and Joining 7/4 (2002) 187-196.

[29] G. Çam, M. Koçak, Progress in joining of advanced materials, International Materials Reviews 43/1 (1998) 1-44.

[30] G. Çam, M. Koçak, D. Dobi, L. Heikinheimo, M. Siren, Prediction of steady-state dilution in multi-pass hardfacing overlays deposited by self-shielded flux cored arc welding, Science and Technology of Welding and Joining 2/3 (1997) 95-101.