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Mechanical behavior of 7085-T7452 aluminum alloy thick plate joint produced by double-sided friction stir welding: Effect of welding parameters and strain rates

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Abstract:

Mechanical behavior of double-sided friction stir welding (DS-FSW) aluminum alloy thick plate joints under various rotational rates and welding speeds tested at different strain rates were investigated. The results show that both the yield stress (YS) and the elongation to failure of DS-FSW joints increase, but the ultimate tensile strength (UTS) of defect-free joints decrease with the decrease of strain rate from 10^{-2} s^{-1} to 10^{-5} s^{-1}. A remarkable reduction in the YS, UTS and elongation to failure presents, particularly at the top slice of 950/60 joint, reaching approximately 65%, 68% and 25% of the BM tested at a strain rate of 10^{-4} $s^{-1}$and fails through brittle fracture. The top slice presents the highest strength and the middle slice has the largest ductility, the same as change laws of joint efficiency and strain hardening behavior among three slices. The best welding parameters is the rotational rate of 300 rpm and welding speed of 60 mm/min due to the higher and the smaller fluctuation of strength and ductility for different slices.

Keywords: Double-sided friction stir welding; Aluminum alloy; Mechanical behavior; Strain rate

1. Introduction

Friction stir welding (FSW), which is invented by The Welding Institute of UK, is a remarkable and potentially useful welding technique and developed in this decade, especially in aerospace and automotive applications involving aluminum alloys [1,2]. For the aluminum alloy thick plate, microstructure and mechanical properties of FSW joints along the thickness direction presented a bigger difference by the conventional single-sided FSW (SS-FSW) process using a relatively large size welding tool [3,4]. So some methods are needed to improve this inhomogeneity of microstructure and mechanical properties. Some reports investigated FSW aluminum alloy joint via cooling condition and post weld heat treatment to enhance the mechanical properties. Zhang et al. [5] reported that the hardness of low hardness zone (LHZ) and strength of FSW 2014Al-T6 joints could not be enhanced by water cooling or improved by post-weld artificial aging. Post-weld T6 heat treatment enhanced the joint efficiency. However, the fine grains present abnormal growth to millimeter-scale in the weld nugget zone (WNZ) and crack tended to develop along the 'S' line at the bottom of the joints while welding speed is high, and this will damage the mechanical properties of the joints [6]. Therefore, the above investigations indicated that the mechanical properties of FSW thick plate joints along the thickness direction could not be improved via water cooling and post weld heat treatment. Meanwhile, it can be concluded from the previous studies that both the rotational rate and the welding speed have a great influence on the microstructure, and this in turn affects the microhardness distribution and mechanical properties [7-9].

Double-sided FSW (DS-FSW) is a novel variant of conventional SS-FSW, employing a small diameter welding tool which welded other side after the first side of weld. Previous research results show that both the larger temperature gradient and the uneven plastic deformation along the thickness direction of plate are easy to produce the inhomogeneous microstructure and significant deterioration of mechanical properties for different slices when using SS-FSW [10,11]. The significant homogeneity of microstructure and mechanical properties can be induced by reducing the temperature gradient and improving the non-uniform plastic deformation after DS-FSW [11,12]. Up to now, few attempts [11-13] about the microstructure evolution and mechanical properties have been made during DS-FSW process. However, the effect of rotational rate and welding speed on the mechanical properties and strain hardening behavior of FSW joint slices along the thickness direction of plate, to the best of our knowledge, is not available in the existing literature. Meanwhile, it is unknown if and to what extent the mechanical properties and strain hardening behavior tested at different strain rates of the slices would change. To further homogenize the microstructure and mechanical properties of FSW thick plate to improve the welding quality, the effect of DS-FSW parameters and strain rate on the mechanical properties along the thickness direction is valuable and necessarily investigated.

In this study, the 12 mm thick 7085-T7452 (Al-Zn-Mg series) aluminum alloy, which are very attractive engineering materials used in aerospace and other engineering applications due to fairly high strength, fracture toughness and excellent resistance to stress corrosion cracking [11], was selected and subjected to DS-FSW at a different rotational rates of 300 rpm, 600 rpm, 950 rpm, and welding speeds of 60 mm/min, 120 mm/min, 180 mm/min. The aim of this work is to investigate the influencing mechanism of different welding parameters and strain rates on the mechanical properties and strain hardening behavior along the thickness direction of FSW joints.

2. Materials and methods

Commercially available Al-Zn-Mg alloy 7085 (12 mm thick) in T7452 temper was used in this study. The nominal chemical composition of the alloy is 7.0-8.0 Zn, 1.2-1.8 Mg, 1.3-2.0 Cu, 0.08 Fe, 0.06 Si and 0.08-0.15 Zr with a balance of Al (wt.%). Tool rotational rates of 300 rpm, 600 rpm, 950 rpm and welding speeds of 60 mm/min, 120 mm/min and 180 mm/min were used. To simplify naming, each joint is called using the corresponding rotational rate and welding speed mentioned in Table 1. 300/60, for example, indicates a joint welded under a rotational rate of 300 rpm and a welding speed of 60 mm/min. The welding tool was characterized by a concave double ring shoulder of 16 mm in diameter, as well as a threaded probe with 7 mm in root diameter, 6.2 mm in tip diameter and 6 mm in length. The title angle of 2.5° was used.

Optical cross section macrographs and microstructural characterization after etching with Keller's reagent were performed using an confocal laser scanning microscope and an optical light microscope (OM), respectively. The microhardness tests were conducted along on the cross-section perpendicular to the welding direction, using a load of 200 g and a dwell time of 20 s. When performing the microhardness maps, points were acquired on a grid of spacing 0.5 mm in the horizontal and vertical directions.

According to ASTM E8 standards, rod-shaped tensile specimens with a gauge length of 25 mm and a width of 6 mm, were machined in the direction perpendicular to the welding direction using electron discharge machine (EDM). The gauge areas of specimens were ground with SiC papers up to 600 grit along the loading axis to smooth the surface and remove cut remarks. The tensile tests were performed out using a fully computerized tensile testing machine at a constant strain rates of 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5} s^{-1} at room temperature. At least three samples were tested at each strain rate for each type of joint. SEM/EDS was used to observe fractures in typical BM and FSW joints.

3 Results and discussion

3.1 Mechanical properties

Fig. 1 shows the effect of strain rates on yield strength (YS), ultimate tensile strength (UTS) and elongation to failure of DS-FSW joints welded at various rotational rates and welding speeds. It is apparent from Fig. 1 that both the YS and the elongation to failure increases with the decrease of strain rate from 10^{-2} s^{-1} to 10^{-5} s^{-1}. However, the UTS of defect-free joints for 300/60, 600/60, 950/60 and 950/120 decrease and an inverse pattern can be obtained for 950/60 joint with an obvious defect. The reason is that the stress increment per unit deformation was reduced with the decrease of strain rate, and which makes it take longer time to reach the fracture strength of the weld material. In addition, with the decrease of strain rate, the stress relaxation and uniformity of the bearing surface for the plastic material become strong during the tensile deformation, and results in the reduction of accumulate peak stress and the increase of fully elastic deformation of the material. However, in the lower strain rate condition, the degree of plastic deformation strengthening, mainly attributed to the decrease of dislocations pile-up impeding dislocation glide, becomes weak when yield occurred [3,4].

Therefore, both the YS and the elongation to failure are enhanced but the UTS decreases with the decrease of strain rate. For the FSW joint with a defect, the higher the strain rate, the greater stress accumulation, the more pronounced the stress concentration due to insufficient time to release stress [14]. Therefore, the joint is easier to reach the critical fracture stress and premature failure occurs prior to arriving at the full capacity of plastic deformation when using higher strain rate during tensile tests. Thus the UTS exhibits lower values at high strain rates, as shown in Fig. 1c.

The top slice shows higher strength than middle and bottom slices tested at the same strain rate, but the middle slice presents higher ductility than the other two slices excepted for 600/60 and 950/60 joints whose middle slice and bottom slice presents higher strength and larger ductility, respectively. Although the strength and the ductility of 950/120 and 950/180 are higher compared with the 300/60, the larger fluctuations among slices is showed in Fig. 1d and 1e. For example, the maximum value of YS, UTS and elongation to failure of BM is 460±2 MPa, 513±1 MPa and 14.9±0.9%, respectively. For the top slices, the corresponding value of 300/60, 950/120 and 950/180 joints are 331±6 MPa, 449±5 MPa and 14.2±0.6%, 348±10 MPa, 459±7 MPa and 11.6±1.8%, 369±22 MPa, 462±28 MPa and 9.4±0.3%, respectively. The same change trend can be found in the middle and bottom slices, as shown in Fig. 1d and 1e.

The larger decreases of the strength and elongation are obtained after welded at a higher rotational rate of 950 rpm and lower welding speed of 60 mm/min, as shown in Fig. 1c. Moreover, the higher strength and elongation are present at the middle slices and the bottom slices, respectively. The maximum value of YS and UTS for 950/60 joint are only 304 MPa, 395 MPa, respectively and the minimum elongation to failure is only 1.6% which is much lower than that of the BM (13.6%) for the same strain rate of 10^{-2} s^{-1}. It also can be seen from Fig 1c-1e that both strength and elongation to failure significantly improve with the increase of welding speed from 950/60 to 950/120 to 950/180. For the DS-FSW joints produced at welding speeds of 60 and 180 mm/min, the maximum values of YS, UTS and elongation to failure are 304 MPa, 395 MPa, 14.4% and 370 MPa, 470 MPa, 12.5%, respectively.

For a constant welding speed (60 mm/min), a lower rotational rate of 300 rpm could help reduce the heat input while a flow stress of stirred plastic materials decreases. Therefore, the plastic material is orderly steady flow and forms a high quality joint. The heat input combined with a rapid decrease in flow stress of stirred plastic materials would elevate [8]. As a results, much more plastic material would be extruded into the WNZ and is easy to produce flaws at a higher rotational rate of 950 rpm and a slower welding speed of 60 mm/min, which will worsen both the strength and ductility of joints, especially the top slice (Fig. 1c). The bottom slices present the lower strength and higher ductility results from the growth and much more dissolution of second phase particles into the aluminum matrix, which is caused by the first weld underwent second thermal cycle from the second weld. Both of the heat input and the plastic strain rate decrease and form the right amount of plastic material while the welding speed increases from 60 to 120 to 180 mm/min under the rotational rate of 950 rpm.

The effect of the ratio of rotational rate and welding speed on joint efficiency is shown in Fig. 2 under different strain rates. The decreasing trend is obtained with the increase of strain rate from 10^{-2} s^{-1} to 10^{-5} s^{-1}. It can be also seen that the joint efficiency of top slice after welding under slow rotational rate of 300 rpm and welding speed of 60 mm/min increases from 85.6 to 88.9 to 92.1% at first, and then decreased to 91.3% for the decrease of strain rate from 10^{-2} to 10^{-5} s^{-1}. The corresponding value of joint efficiency for bottom slice is 81.1, 83.9, 88.1 and 87.3%, respectively. However, the joint efficiency of top slice and bottom slice is 75.8, 66.8, 77.5, 80.1% and 75.1, 76.9, 77.7, 77.9%, respectively, after welding under fast rotational rate of 950 rpm and slow welding speed of 60 mm/min. When the welding speed reaches 180 mm/min and the same rotational rate as the former, the value of top slice is 86.5, 86.8, 91.9, 94.7% and 83.7, 88.1, 88.5, 92.4%, respectively. Meanwhile, the change of joint efficiency vs. strain rate for the different slices presents a larger fluctuation after welding under the highest rotational rate of 950 rpm than that of 300 rpm and 600 rpm. This results reveal that the best welding parameters is the rotational rate of 300 rpm and welding speed of 60 mm/min.

3.2 Strain hardening behavior

To understand the effect of strain rate on the strain hardening behavior of BM and FSW slices, the strain hardening capacity (H_c) and the strain hardening exponent (n) were investigated in this study. H_c of a material can be construed as a ratio of the UTS (σ_{UTS}) to the YS (σ_{YS}). The n is a measurement of the ability of a metal to strain hardening. The larger the value of n is, the greater the strain hardening is at a given amount of plastic strain [15]. Afrin et al. [16] defined the hardening capacity in the following equation (1) and the strain hardening exponent in the uniform plastic deformation can be defined as the following formula (2):

$$H_c = \frac{\sigma_{UTS} - \sigma_{YS}}{\sigma_{YS}} = \frac{\sigma_{UTS}}{\sigma_{YS}} - 1 \tag{1}$$

$$\sigma = K\varepsilon^n \tag{2}$$

where K is the strength coefficient, σ is the true stress and ε is the true strain. The n-value of strain hardening exponent is calculated by the slope in the plot of Log σ vs Log ε.

Fig. 3 shows the hardening capacity and strain hardening exponent of BM and FSW slices tested under various strain rates from 10^{-5} s^{-1} to 10^{-2} s^{-1}. The results show that both the hardening capacity and the strain hardening rate of joint increase significantly compared with BM. The reason is fact that the material of weld exhibits certain softening during the FSW process and the decrease of YS is larger than that of UTS. Moreover, both of H_c and n increase with the increase of strain rate, which is largely due to the slope of the YS while it is slightly steeper than that of the UTS with the increase of strain rate from 10^{-5} s^{-1} to 10^{-2} s^{-1} (Fig. 1). Meanwhile, the H_c value increases from the top slice to the bottom slice. Since the decrease trend of YS can be observed, top slice presents lower H_c value than that of middle and bottom slice, maximum H_c value is obtained at the bottom slice according to Eq. (1). And the same increase trend is obtained for the strain hardening exponent of 300/60 and 600/60 joints. However, the random change of n is shown in the joint after welding at the higher rotational rate of 950 rpm. There forms too much more plastic metal and undergoes uneven mechanical forging at the higher rotational rate. These are in agreement with the change of mechanical properties. Although the peak temperature and the degree of mechanical deformation are reduced by the increase of welding speed to 180 mm/min, the asymmetry of the higher mechanical properties and the lower strain hardening behavior are obtained after testing at various strain rates. This is further confirmed that the optimization of welding parameters is a rotational rate of 300 rpm and a welding speed of 60 mm/min.

3.3 Microhardness distribution

Microhardness maps are shown in Fig. 4 from the transverse weld cross sections, along with the corresponding hardness profiles in Fig. 5 across the mid-plate thickness of each weld. The base material (BM) had an average hardness of 155 HV. Softened heated affect zone (HAZ) relative to BM and other weld zones are observed for all samples and is the lowest hardness zone (LHZ), corresponding to the 300/60 and 950/180 joints. The reason is that the grain size increases (Discussed in the following Fig. 8) and precipitate strengthening effect are dramatically reduced caused by the grain coarsening or precipitate dissolving [11], respectively. For the best welding parameters, slow rotational rate of 300 rpm and welding speed of 60 mm/min, the microhardness of the WNZ fluctuates between 130 and 150 HV, which is lower than that of the BM. The minimum value approximately 100 HV presents in HAZ after FSW. Hence, it is no wonder all the free-flaw of joints are fractured in HAZ. However, the LHZ is in the whole first weld for 950/60. The value in WNZ, thermal-mechanical affected zone (TMAZ) and WNZ is 100, 95 and 90 HV, respectively. The microhardness profile in the whole first weld tends to a lower horizontal line, as shown in Fig. 5. The softening for 950/60 is attributed to the high temperature thermal cycling and the relatively long high temperature residence time during DS-FSW process. When the welding speed increases to 180 mm/min, the microhardness in HAZ, lowest hardness zone, shows a significant hardness recovery by about 20 HV, resulted in the formation of typical 'W' shaped hardness profile again. These hardness results are in complete accordance with the microstructure results after welding under the corresponding rotational rate and welding speed. Meanwhile, it is worth noting that the whole hardness level of 950/180, presenting a significant inhomogeneity across the mid-plate thickness and a larger fluctuation in WNZ and HAZ (Figs. 4c and 5), is relatively higher than that of 300/60. Thus, it is further confirmed that the best welding parameters is rotational rate of 300 rpm and welding speed of 60 mm/min in this research.

3.4 Weld formation

Fig. 6 shows the cross-sectional macrostructures of joints produced at different rotational rates and welding speeds. BM and three main welding zones, that is, WNZ, TMAZ and HAZ, can be easily distinguished in these pictures. A indistinct transient boundary between the WNZ and TMAZ is shown on the retreating side (RS), while a more sharp boundary can be seen on the advancing side (AS). Which is due to different plastic flow patterns and degree of plastic deformation caused by the various temperature and shear force on different sides of the welding tool. Similar results was obtained in the previous references by Xu et al. [17] and Esmaily et al. [18]. Defect-free DS-FSW joint can be produced at all parameters except 950/60. There is no appearance of "onion rings" in the WNZ, but the tunnel defect, S-line and larger flash on the RS can be seen in the 950/60 joint, and are pointed by black arrows in Fig. 6c. Too much plastic metal could not be normal and orderly flow when welded at the higher rotational rate and the slower welding speed. As a consequence, the cavity on the AS could not be backfilled by the flow around the tool of RS and formed the tunnel defect, as reported by Xu et al. [19]. Meanwhile, the higher rotational rate and the slower welding speed, the more plastic material forms, the greater flash obtains due to the constant of extrusion die between the welding tool and the unplasticized metal.

It also can be seen from Fig. 6 that a shallow region of affected material at the crown of second weld is produced by the pressure of the rotating shoulder against the plate surface during FSW process, especially for the increase of rotational rate from 300 to 950 rpm. While no shallow region is shown at the crown of first weld due to the extrusion from the second weld. As it can be seen, dimensions of WNZ are different in various joints. The widths of the first and second weld increase with the increase of rotational rate from 300 to 600 to 950 rpm when using the constant welding speed of 60 mm/min. While the trend to decline is shown in the increase of welding speed from 60 to 120 to 180 using the same rotational rate of 950 rpm. Almost all of the first welds have a more narrow width compared with the corresponding second welds, as shown in Fig. 6. For example, the widths of the first and second weld are approximately 15.0 and 15.4 mm, 15.7 and 16.3 mm, 16.4 and 16.3 mm, 16.2 and 15.5 mm, 15.3 and 15.4 mm corresponding to the 300/60, 600/60, 950/60, 950/120 and 950/180 joints, respectively. The weld zone gradually becomes narrower below the weld surface and the minimum width of weld zone occurs near the midplane of the plate thickness, where both weld roots passes overlap. It also can be found that the second weld shifts to the left obviously and producing a noticeable asymmetry for the higher rotational rate of 950 rpm.

The dimension of WNZ is proportional to the peak temperature and the holding time of material at high temperature, i.e. the higher the peak temperature, the longer the holding time at high temperature, the larger WNZ is. Meanwhile, it is well accepted that the heat input is enhanced by the increase of rotational rate or the decrease of welding speed [14]. According to these theory, the higher rotational rate or the slower welding speed generates the higher frictional heat, resulting in heating up larger area of the surrounding materials. So different dimensions of WNZ are observed in the corresponding joints. Moreover, the larger shallow region at the crown of first weld is easily to be formed when apply higher rotational rate. During the second welding process, it has to be compacted the gap of different sizes between the top surface of first weld and the backing plate, in order to achieve high quality welding. The rotated welding tool title angle leads to larger shifts to the left for the second weld compared with the first weld along with the increase of rotational rates.

3.5 Microstructure characteristics

In order to characterize microstructural evolutions, different zones of various joints were observed by the optical microscopy, as shown in Figs. 7 and 8. It can be seen from Fig. 7 that the microstructures in WNZ are characterized by fine and equiaxed structures due to the dynamic recrystallization caused by high temperature and severe plastic deformation. The grain size in the WNZ obtained at 300 rpm is finer than that at higher rotational rate of 950 rpm, since heat input increases by the increase of rotational rate. Moreover, as can be seen, the first welds for 950/60 and 950/180 present larger grain size compared with the second weld. This is because grains experience secondary growth caused by higher heat input during second welding process under the higher rotational rate. However, the slight change can be observed for both welds of 300/60. So the above microhardness distribution of WNZ can be obtained according to Hall-Petch relationship. This also suggests that it is difficult to fracture in WNZ except for the occurrence of tunnel defect.

The TMAZ, the transition zone between the WNZ and the HAZ, experiences medium strain rates and high temperatures during DS-FSW process. As it is shown in Fig. 8a, elongated grains which are produced by the plastic shear stress along the plastic flow of material and some large recrystallized grains are achieved. It also can be found that the degree of resrystallization and grain growth increase with the increase of rotational rates from 300 rpm to 950 rpm.

The HAZ is affected by the thermal cycle and experiences no plastic deformation. Notably coarsened grains are observed in HAZ, as shown in Fig. 8b. The grain in HAZ of 950/60 exposed to higher thermal cycle becomes basically equiaxed compared to the 300/60 and 950/180, which is mainly attributed to the obviously grain growth along the short direction of the initial large elongated and pancake-shaped grains of BM. As a result, the age softening of HAZ is much more significantly in comparison with WNZ and TMAZ, and the minimum hardness decreases with the increase of rotational rates. Tensile fractures are prone to occur in HAZ for free flaw joint.

3.6 Fracture behavior

As illustrated in Fig. 9, the shear fracture mode at about 45° to the tensile axis occurs in the HAZ of AS or RS. Moreover, there is a considerable necking in failure zone. This is because the region is the LHZ observed from the above microhardness maps and curve (Figs. 4 and 5). However, the tensile strength and the elongation to failure of top slice for 950/60 joint significantly decreases and the fracture occurs in the WNZ as well as no necking due to the tunnel defect which becomes the initiation of crack easily. This kind of defect results in bad ductility, as shown in Fig. 6c.

Typical fracture feature of BM and different slices along the thickness of 300/60 joint tested at both strain rate of 10^{-2} $s^{-1}$and 10^{-5} s^{-1} are shown in Fig. 10. It can be seen from the Fig. 10a and 10b that the tensile fracture surface of BM presents much more deep dimples and unsharp tearing ridges full of micropores at the slow strain rate of 10^{-5} s^{-1} in comparison with the fast one 10^{-2} s^{-1}. This result demonstrates that the ductility of aluminum alloy BM decreases with the increase of strain rate from 10^{-5} s^{-1} to 10^{-2} s^{-1}, which is consistent with the result in Fig. 1.

It also can be found from Fig. 10c-e that the slices of 300/60 joint present a typical ductile fracture and the top slice has a little more dimples with various size and shapes compared to the middle and bottom slices.

Tensile failure of defect-free joints, including the middle and bottom slices of 950/60 joint, are completely accords with the characteristics of ductile fracture accompanied by micro-void coalescence mechanism and formation of dimples of all sizes on the fracture surface. Fracture can initiate from the small surface scratch or stress concentrations and then propagate across surface with the least resistance under the action of shear stress.

According to the Fig. 11a, fracture surface is relatively featureless and did not show dimples for the top slice of 950/60 joint under higher strain rate of 10^{-2} s^{-1}. However, a clear sign of brittle fracture, such as cleavage pattern, can be obtained. The major reasons must be owing to the stress concentration around the defect and the decrease of effective bearing cross section caused by the formation of tunnel defect in the WNZ of second weld, thereby the joints achieve no yielding fracture and elongation decrease dramatically.. However, the failure is a kind of ductile fracture for the middle and bottom slices without defects (Figs. 11b and 11c) and the higher yield and tensile strength without any remarkable reduction of ductility are obtained, as shown in Fig. 1c. Meanwhile, the fracture surface of top slice consists of many dimples with various sizes and shapes when tested at slow strain rate of 10^{-5} s^{-1}, which is a sign of a typical ductile fracture, as shown in Fig. 11d. This is mainly due to the presence of many tear ridges, reflecting the ability of the material to bear the tensile stress after beginning the formation of microvoid coalescence. Lacking of the tear ridges demonstrates that the brittle specimens would fracture soon after commencement of microvoid coalescence [20].

Mao et al. [4] also reported that similar results for different slices of FSW 7075-T6 aluminum alloy thick plate joints.

4. Conclusions

In this research, DS-FSW was carried out on a 7085-T7452 Al-alloy thick plate, and the effects of rotational rate and welding speed on the microstructure, microhardness and tensile behaviors under various strain rates were investigated. Based on the above results obtained, the following conclusion can be drawn:

1. With the decrease of strain rate from 10^{-2} s^{-1} to 10^{-5} s^{-1}, the YS and the elongation to failure of DS-FSW joints increase, but the UTS of defect-free joints decrease and a inverse pattern can be obtained for 950/60 joint with an obvious defect. Among three slices excepted for 600/60 and 950/60 joints, the top slice presents the highest strength but the middle slice has the largest ductility. The same change laws of joint efficiency and strain hardening behavior have been obtained.

2. A remarkable reduction in the YS, UTS and elongation to failure occurred, particularly at the top slice of 950/60 joint, reaching approximately 65%, 68% and 25 % the YS, UTS and ductility of the BM under strain rate of 10^{-4} s^{-1}. Fracture surface for the top slice is relatively featureless and did not show dimples while ductile fracture occurs at the middle and bottom slices without defects. This is mainly attributed to the presence of tunnel defect in the WNZ of second weld.

3. Within the welding parameters in this study, the best one is the rotational rate of 300 rpm and welding speed of 60 mm/min due to the smaller shallow region at the crown, no shift to the left for the second weld, the homogeneous finer recrystallized grain and the smaller

fluctuation of mechanical properties and microhardness for different slices.

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