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Technical Report

Effect of differential heat treatment on the formability of aluminium tailor welded blanks

N. Bhanodaya Kiran Babu [a,*], M.J. Davidson [a], A. Neelakanteswara Rao [a], K. Balasubramanian [b], M. Govindaraju [b]

[a] Mechanical Engineering Department, National Institute of Technology, Warangal, India
[b] Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad, India

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ABSTRACT

Tailor welded blanks (TWBs) are blanks that are tailor made to suit the required function. They are made by joining blanks of different thicknesses, materials, coatings, etc. The forming behaviour of such TWBs will be different from the conventional blanks, as TWBs with different strength levels will be subjected to the same forming loads but will result in unequal deformation values. The present work is aimed at studying the formability behaviour of TWBs of two different materials namely AA6061 and AA2014. The blanks were made by friction stir welding process at different rotational speeds, welding speeds and tool tilt angles on a vertical head milling machine. The formability of the TWBs and the base materials has been studied before and after solution heat treatment and analysed with the help of Limiting Dome Height (LDH) test. A differential heat treatment approach has been followed, which is unique in this work. From the results, it was found that the formability of heat treated TWBs were higher than those of base materials and untreated TWBs.

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1. Introduction

Tailor welded blanks are made with different sections of sheets, of different materials with different thickness, coatings, etc. TWBs are used mainly in automotive and aerospace applications, wherein a strong and a weak material are required to be joined optimally such that cost saving can be made by using materials of different strength levels at places where it is required. The joined material will then be formed into the required structure. However, the forming of the TWB with a stronger and a weaker material will not be easy as the weaker material will respond well to the forming load and the stronger material will not. An uneven deformation takes place and the material fails before reaching the intended elongation. The formability of TWB depends on many factors and researchers around the globe have studied different aspects of them in their works.

Researchers make TWBs through processes such as laser welding, friction stir welding, gas metal arc welding, etc. [1–4], Koklu [5] used both metal inert gas and laser welding with antilock breaking system in deep drawing to improve the formability of welded blanks. Romhanji and Grabulov [6] developed welded blanks with the GTAW and SMAW techniques and revealed that the formability of welded blanks in biaxial conditions is lower when compared to the base metals. Some researchers made TWBs using friction stir welding technique to join dissimilar aluminium alloys [7–9]. Karthikeyan et al. [10] studied biaxial stretch forming on welded blanks made with aluminium alloy A319. The authors used friction stir processing technique to improve the formability. Jain et al. [11] have conducted deep drawing experiments to find the drawability of dissimilar aluminium alloys of AA5754 and AA6111. Padmanabhan et al. [12] have produced TWBs with the combination of aluminium and steel sheets and formability properties of welded blanks were evaluated with finite element analysis. Panda and Ravi Kumar [1] have performed formability analysis of welded blanks in plane-strain stretch forming condition. Ganesh Narayanan and Naik [13] have formulated new failure criteria to predict the formability of unwelded and tailor welded blanks. Dilmec et al. [14] have developed the forming limit diagram of aluminium alloy AA2024 and studied the effect of sheet thickness and anisotropy on the welded blanks. It has been observed from the literature that some researchers have studied the failure analysis of aluminium alloys blanks with the help of forming limit curves [15,16]. Aghaie khafri [17] used homogenized AA8011 aluminium alloy to examine the formability characteristics of uniaxial and biaxial strain forming conditions.

From the existing literatures, it was observed that no work has been reported on the formability of tailor welded blanks made of AA6061 and AA2014. Hence in the present work, dissimilar welded blanks have been made from heat treated and non heat treated aluminium alloys. Two different aluminium alloys with varied

* Corresponding author. Tel.: +91 9010458810.
E-mail addresses: bhanodaya@nitw.ac.in (N. Bhanodaya Kiran Babu), mjdavidson2001@yahoo.co.in (M.J. Davidson).

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mechanical properties such as AA6061 and AA2014 have been chosen as the base materials. Efforts have been made to improve the ductility of the joint by varying the friction stir process parameters as earlier literatures have revealed that the ductility will be maximum at optimum process parameters. Experiments were performed as per Taguchi L9 orthogonal array experimental plan. Formability tests have been conducted on all the samples made as per the experimental plan. Blanks made of AA2014 alloy were found to have far less formability than AA6061 alloy. As AA2014 is a natural aging material, a differential heat treatment technique has been followed in this work to improve the formability of the joints which is unique in this work. AA6061 was taken in the T6 condition and AA2014 was solution treated. The TWBs were made five days after solutionizing the AA2014 samples as it was found that from three to five days, the alloy age hardened by precipitation process and attained more or less equal strength as that of AA6061 alloy.

2. Experimental work

2.1. Materials

The base materials used for the present study are AA6061 and AA2014 aluminium alloy sheets. The composition of AA6061-T6 and AA2014-T6 alloys are given in Table 1. Mechanical properties of the base materials are given in Table 2. AA2014 is a natural age hardening material. The elongation at break value of AA6061 is 22% and that of AA2014 is 12%.

2.2. Heat Treatment

Initially, the formability tests on the TWB were performed without performing heat treatment. The formability was very low and the blanks cracked on the stronger side i.e. on AA2014 side. Huge weld line movements were experienced and the blanks were not forming evenly. Tensile test performed on the blanks revealed that the percentage elongation of AA6061 to be 22% and that of AA2014 to be 12%. To make the blank deform evenly, the stronger blank, AA2014 aluminium alloy was solution heat treated at 495 °C for 1 h in an electrical furnace excluding the furnace heating time before friction stir welding. AA2014 material, being a natural aging material, gave different elongation levels at different days after the treatment. Tensile testing was done on solutionized AA2014 blanks and the tensile test was performed at different days namely one day, two days, three days, four days and five days after the solution treatment. A total elongation of 22% was achieved on a sample tested after five days. As the percentage elongation of untreated AA6061 alloy and treated AA2014 sample tested after five days had closer total elongation values, it was planned to make the TWB with an untreated AA6061 alloy and solutionized AA2014 alloy. The formability tests were conducted on the TWBs on the fifth day.

2.3. Orthogonal array

The Design of Experiments (DoE) concept has been followed in the present investigation to reduce the number of experiments. Taguchi orthogonal array with three input parameters and three

Table 1
Chemical composition (wt%) of base materials.

Elements	Mg	Si	Cu	Ti	Cr	Al
6061-T6	0.60	0.76	0.025	0.017	0.043	Balance
2014-T6	0.46	0.75	3.98	0.026	0.017	Balance

Table 2
Mechanical properties of base materials.

Base Material	Yield strength (MPa)	Tensile strength (MPa)	Percentage elongation (%)	Micro hardness (Hv)
AA6061	198	273	22	115
AA2014	402	454	12	165

Table 3
Input process parameters and their three levels.

Sl. no	Parameters	Units	Low level	High level
1	Rotational speed	rpm	900	1400
2	Welding speed	mm/min	16	32
3	Tool tilt angle	degree	0	2

Fig. 1. Hydraulic press used in the present work.

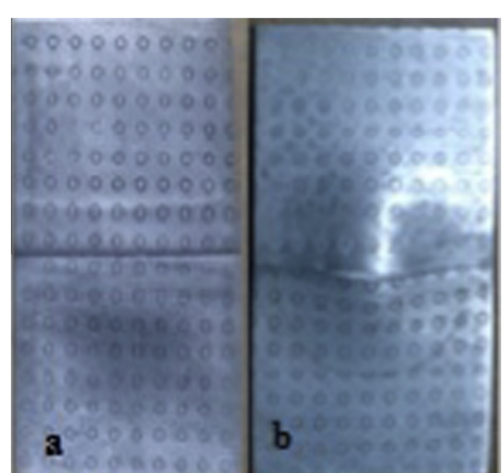

Fig. 2. Tailor welded blanks (a) before forming and (b) after forming.

levels has been used to perform the welding. The input process parameters chosen are Rotational Speed (RS), Welding Speed (WS) and Tool Tilt Angle (TA). The input parameters and their three levels used in the present work are given in Table 3. Nine combinations of process parameters were obtained by varying the three parameters in three discrete levels. The TWBs were prepared by friction stir welding method and as per the Taguchi experimental array. The limiting dome height is the quality response for TWBs. The analysis of variance (ANOVA) was applied to determine the influence and contribution of each process parameter on the quality response of TWBs.

2.4. Preparation of TWBs

The AA6061 and the heat treated AA2014 sheets were cut into 300 × 75 × 3 mm blanks and were fixed in the table of a vertical milling machine. The sheets were clamped to the bed tightly so that they stay in position during the welding process. A non-consumable rotating tool with a pin of H-13 tool steel material was used as the FSW tool. The tool was made with a shoulder diameter of 20 mm, a tapered threaded pin profile of 6 mm diameter and with a pin length of 2.5 mm.

2.5. Limiting Dome Height (LDH) Test

The use of friction stir welding and dome height test to determine the mechanical and formability properties of dissimilar welded blanks has been reported earlier [8,9]. LDH test has been used successfully by different researchers to find the formability of different metals [18,19]. In the present work too, LDH test has been used to evaluate the formability of the TWBs made of heat treated and non heat treated blanks. The tests were conducted on samples of varied widths, till the width of the samples simulated plane strain condition. As a blank of size 100 mm × 60 mm simulated plane strain condition, rectangular specimens of size 100 mm × 60 mm were cut from the welded sheets and formed with a 36 mm diameter punch. The LDH test was carried out on a 50 ton hydraulic press (Fig. 1) at a punch speed of 0.3 mm/s. A data logger was used to record and store the dome heights and the forming loads during the tests. Fig. 2a and b shows the tailor welded blanks before and after forming.

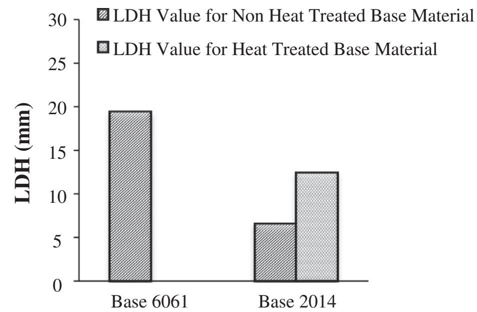

Fig. 3. Limiting dome height of non heat treated and heat treated base materials.

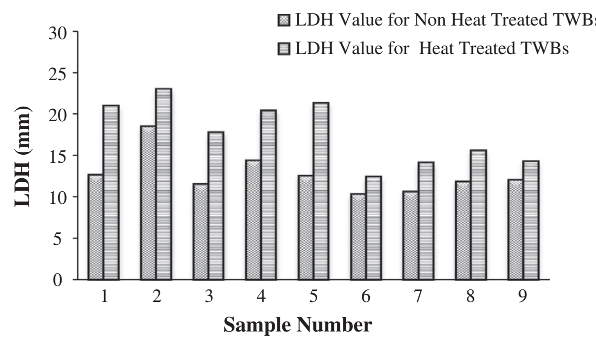

Fig. 4. Limiting dome height of non heat treated and heat treated welded blanks.

3. Results and discussion

3.1. Evaluation of mechanical and formability properties:

The mechanical and formability properties of non heat treated and heat treated welded blanks were measured and are summarized in Tables 4 and 5 respectively. The tensile specimens were

Table 4
Mechanical and formability properties of non heat treated welded blanks.

Sample no.	Rotational speed (rpm)	Welding speed (mm/min)	Tool tilt angle (°)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	LDH (mm)	*n*	1/YR	Micro hardness (MPa)
1	900	16	0	139	169	6.0	12.6	0.159	1.215	83
2	900	24	1	141	174	5.4	18.5	0.224	1.235	104
3	900	32	2	152	183	5.9	11.5	0.142	1.203	98
4	1150	16	1	134	164	2.5	14.4	0.198	1.223	81
5	1150	24	2	151	183	5.0	12.5	0.149	1.211	105
6	1150	32	0	147	174	4.4	10.3	0.120	1.183	77
7	1400	16	2	141	172	5.8	10.6	0.125	1.219	95
8	1400	24	0	148	176	5.6	11.8	0.140	1.190	98
9	1400	32	1	142	174	5.1	12.0	0.139	1.225	80

Table 5
Mechanical and formability properties of heat treated welded blanks.

Sample no.	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	LDH (mm)	*n*	1/YR	Micro hardness (MPa)
1 (900-16-0)	147	181	5.8	21.0	0.232	1.231	85
2 (900-24-1)	148	183	6.8	23.0	0.251	1.236	107
3 (900-32-2)	160	192	6.4	17.8	0.196	1.212	103
4 (1150-16-1)	139	168	6.1	20.4	0.204	1.207	91
5 (1150-24-2)	147	180	6.2	21.3	0.233	1.224	104
6 (1150-32-0)	148	179	5.1	12.4	0.176	1.201	83
7 (1400-16-2)	146	177	6.0	14.1	0.166	1.210	98
8 (1400-24-0)	146	178	5.6	15.6	0.185	1.202	100
9 (1400-32-1)	149	180	5.0	14.3	0.179	1.208	89

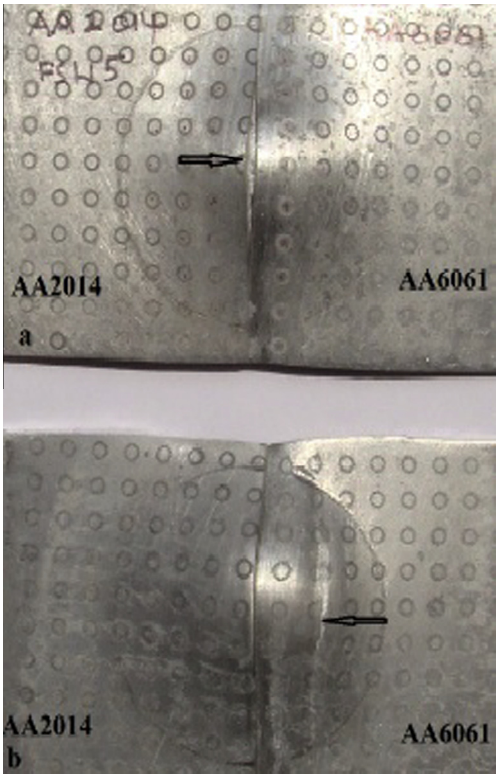

Fig. 5. The tailor welded blank that is formed (a) non heat treated and (b) heat treated.

prepared as per ASTM: E8/E8M-13a guidelines to evaluate the mechanical properties of the welded blanks. The tensile strength of the heat treated welded blanks is higher than the non heat treated welded blanks. However, solutionizing and natural aging of AA2014 base material improved the tensile strength of the heat treated welded blanks.

Fig. 3 shows the LDH test results of AA6061 and AA2014 base materials and heat treated 2014 base material. The limiting dome height of AA6061 base material is 19.4 mm and for AA2014 base material it is 6.2 mm. The LDH value of the heat treated AA2014 base material is 12.4 mm. This shows that an improvement in the formability could be achieved after heat treatment. Fig. 4 shows the LDH of various welded samples. It is observed that all the welded blanks show an improvement in the LDH value after heat treatment. The formability of the heat treated blanks are better than the non heat treated blanks for all the process parameters conditions. The difference in formability achieved by solution treatment is shown in Fig. 5a andb. The welded blank formed without heat treatment is shown in Fig. 5a and b shows the formed blank that was heat treated.

The formability characteristics of any welded blank is a function of work hardening component (n) and work hardening capacity (1/YR) [18,20]. Figs. 6 and 7 shows the relationship between LDH and work hardening component and LDH and work hardening capacity respectively. From Fig. 6a and b, it was observed that there is a linear relationship between the LDH value and work hardening component. The LDH increases linearly with work hardening component for both heat treated and non-heat treated welded blanks. Hence large work hardening component is required for better formability. The LDH value is also related with the inverse of Yield Ratio (YR = yield strength/tensile strength). From Fig. 7a and b, it was observed that there is a linear relationship between the LDH and work hardening capacity. The LDH value increases linearly with work hardening capacity values. These results are matching with the results of Kang et al. [20].

The load and limiting dome height curves registered in data logger during LDH test of the non heat treated and heat treated welded blanks are shown in Fig. 8a and b respectively. It is observed from the Fig. 8a and b that the heat treated blanks can withstand more loads

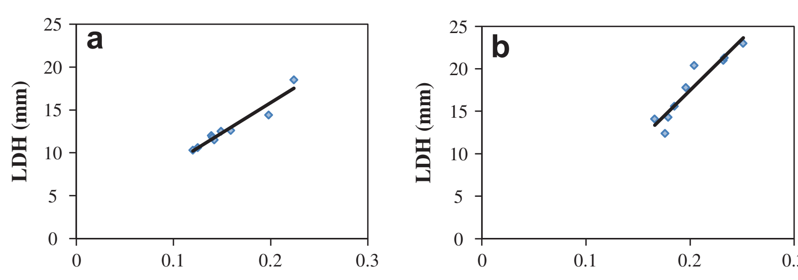

Fig. 6. Variation of LDH with n for (a) non heat treated and (b) heat treated welded blanks.

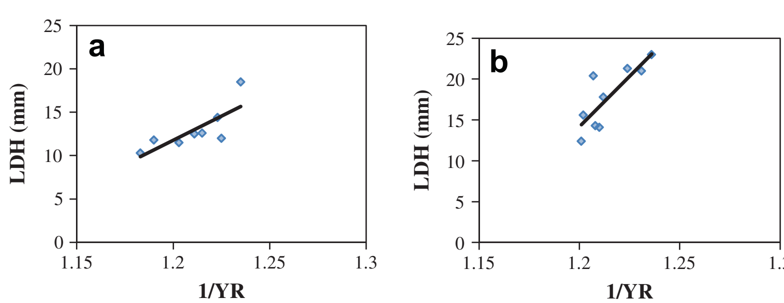

Fig. 7. Variation of LDH with 1/YR for (a) non heat treated and (b) heat treated welded blanks.

and can achieve more elongation. The LDH of all the samples improved after the heat treatment cycle as it is evident from Fig. 8b.

3.2. Influence of process parameters on LDH quality response:

The main effects plot of LDH values for rotational speed, welding speed and tilt angle are shown in Fig. 9a–c. These process parameters have a significant influence on the formability response [18]. A decrease in formability was experienced when the tool rotational speed was increased from 900 to 1400 rpm. The increase in tool rotational speed has increased the frictional force on the blanks thereby increasing the heat input. As this has promoted grain growth, poor formability has been experienced after increasing the speed from 900 to 1400 rpm. The change in welding speed from 16 to 24 mm/min has resulted in increased formability, and change in welding speed from 24 to 32 mm/min has resulted in a decrease in formability. The friction stir welding process promoted grain refinement along the weld line. However, sufficient time must be given for the metal to promote grain refinement. Sufficient dwell time is required for the grains to refine at any particular welding speed. Higher welding speed and rotational speed have resulted in grain growth and insufficient time for the grains to refine. The change of tool tilt angle from 0° to 1° has increased the formability and change of tool tilt angle from 1° to 2° has decreased the formability. The tool tilt angle has made it possible for the metal to

Table 6
Results of ANOVA analysis for LDH quality response.

Process parameter	Degree of freedom	Sum of squares	Adj. mean sum of squares	F-ratio	*P*	% Contribution
(1) For LDH of non heat treated welded blanks						
RS	2	11.58	5.79	12.21	0.076	23.40
WS	2	13.60	6.8	14.34	0.065	27.48
TA	2	23.34	11.6	24.61	0.039	47.17
Error	2	0.95	0.47			1.91
Total	8	49.48				100
(2) For LDH of heat treated welded blanks						
RS	2	53.12	26.56	6.23	0.138	45.70
WS	2	41.94	20.97	4.92	0.169	36.08
TA	2	12.62	6.31	1.48	0.403	10.85
Error	2	8.52	4.26			7.33
Total	8	116.22				100

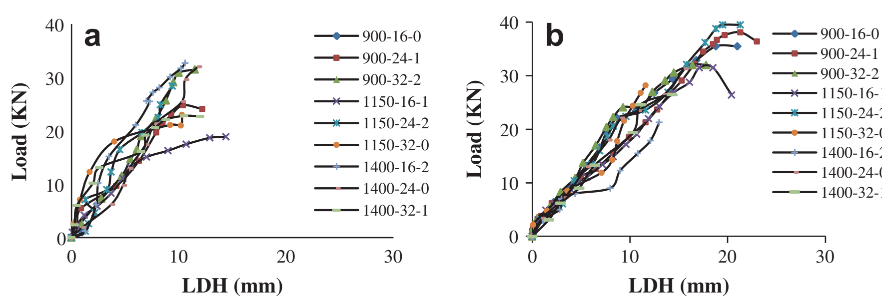

Fig. 8. Load and limiting dome height diagram for (a) non heat treated welded blanks and (b) heat treated welded blanks.

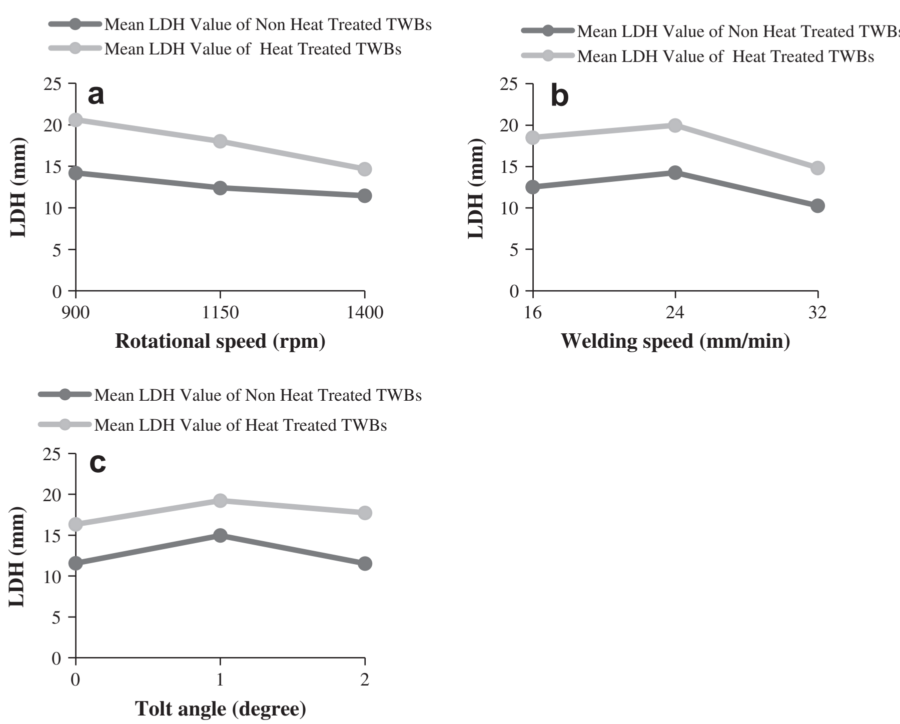

Fig. 9. Main effects plot of LDH values for (a) rotational speed (b) welding speed and (c) tilt angle.

move around the friction stir welding tool in a tilted conical profile enabling the metal to mix well around the pin. This has resulted in a better mixing of the metal that is being joined and has resulted in better formability when a tool tilt angle of 1° has been used. However, when the tool tilt angle was increased to 2°, the cohesion of the metal being joined has been affected because of increased movement of the stirred zone in the vertical direction, resulting in poor formability. The optimum process parameters condition for welded blanks are rotational speed of 900 rpm, welding speed of 24 mm/min and tilt angle of 1°. At this process condition, a favourable heat input for softening and dynamic recrystallization of grains at nugget zone has been experienced resulting in better formability.

ANOVA analysis was done to know the statistical significance of the input process parameters on the quality response of TWBs. The results of ANOVA analysis is illustrated in Table 6. It was observed that for the non heat treated welded blanks, the TA (47.17%) has a high percentage of contribution on LDH response compared with WS (27.48%) and RS (23.40%). It was also observed that for the heat treated welded blanks, RS (45.70%) has a highest percentage of contribution on the LDH response compared with WS (36.08%) and TA (10.85%).

3.3. Influence of process parameters on microhardness quality response

Vickers hardness tester was used to measure the microhardness across the cross section of welded blanks. Microhardness results indicate that the weld zone is softer than the base material. The main effects plot for microhardness for non heat treated and heat treated welded blanks are shown in Figs. 10 and 11 respectively. A decrease in hardness was observed with increasing rotational speed from 900 to 1150 rpm and a small improvement in hardness was observed when increasing the rotational speed from 1150 to 1400 rpm. At 900 rpm the tool pin generates sufficient heat to soften the material. An increase in hardness was observed when the welding speed was increased from 16 to 24 mm/min, and a decrease in hardness values was observed when the welding speed was changed 24 to 32 mm/min. At 24 mm/min sufficient time was available for the rotating tool to soften the material and grain refinement. An increase in hardness is observed when the tool tilt angle is increased from 0° to 2°.

3.4. Microstructural characterization of the welded blanks

The cross section of the weld was analysed by following standard metallurgical procedure. The samples were polished and etched with Keller's reagent to reveal the existence of different zones. The specimen's macrostructure and microstructure was analysed by using optical microscope. Macrostructure of a typical welded blank is shown in Fig. 12. The complete welded area is divided into four zones, namely the weld zone (WZ), thermo mechanical affected zone (TMAZ), heat affected zone (HAZ), and base metal. Weld zone is the region that undergoes dynamic recrystallization and new fine grains are formed due to mechanical action of the rotational tool during the welding process. In TMAZ, the process of recrystallization will be less due to insufficient deformation. In the HAZ, there will be no plastic deformation and

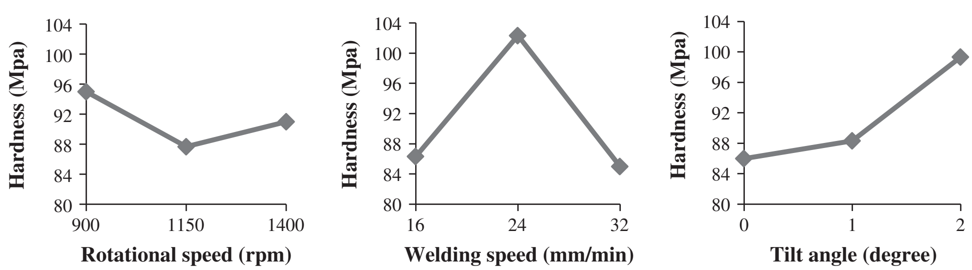

Fig. 10. Main effects plot of microhardness for non heat treated welded blanks.

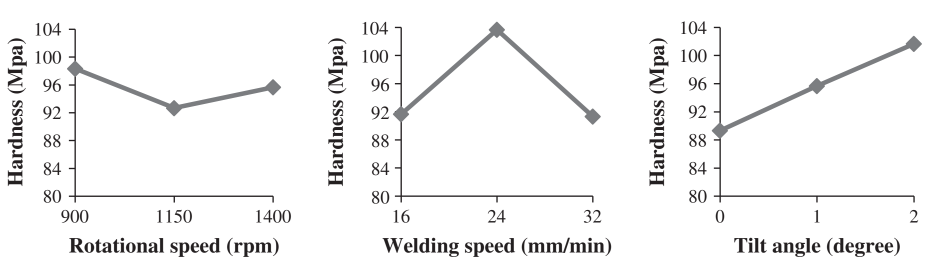

Fig. 11. Main effects plot of microhardness for heat treated welded blanks.

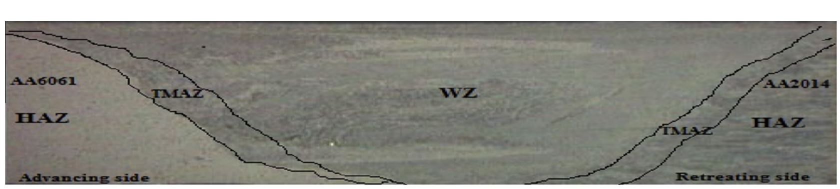

Fig. 12. Cross section of the welded blank with different weld zones.

the grains will be the same as that of the base material. Adjacent to HAZ, there is base material. The macrostructures of the welded blanks were analysed in all the welding parameters conditions. Macrostructures of the welded blanks of non heat treated tailor welded blanks (TWB) and heat treated tailor welded blanks (HTWB) are shown in Figs. 13 and 14 respectively. AA2014 aluminium alloy appears dark in colour than the AA6061 alloy. As it is evident from the macrostructures, the weld zone has not formed properly for the non heat treated blanks. Because of non uniform strength the process parameters chosen for the blank was not good enough to form a good joint between the blanks. The materials have not mixed up properly with the stirring effect of the tool, which is essential for a good joint. However, an examination of the macrostructures of the joints formed with heat treated blanks, revealed the presence of good welded zones in all except few process conditions. For example, the macrostructure of the sample Fig. 14f, proper mixing of the alloy has not taken place and the formability was found to be low for this case.

Fig. 15a and b shows the microstructure details of the AA6061 and AA2014 base materials respectively. The microstructure of AA6061 consists of few Mg_2Si precipitates and the structure of the AA2014 aluminium alloy consists of some insoluble particles such as Fe, Mn, Si, Al particles and $CuAl_2$ particles in a solid solution matrix. Fine precipitates of $CuAl_2$ were found throughout the matrix in the naturally aged AA2014 sample (Fig. 15c). Fig. 15d–f shows the weld zone microstructure of the dissimilar welded

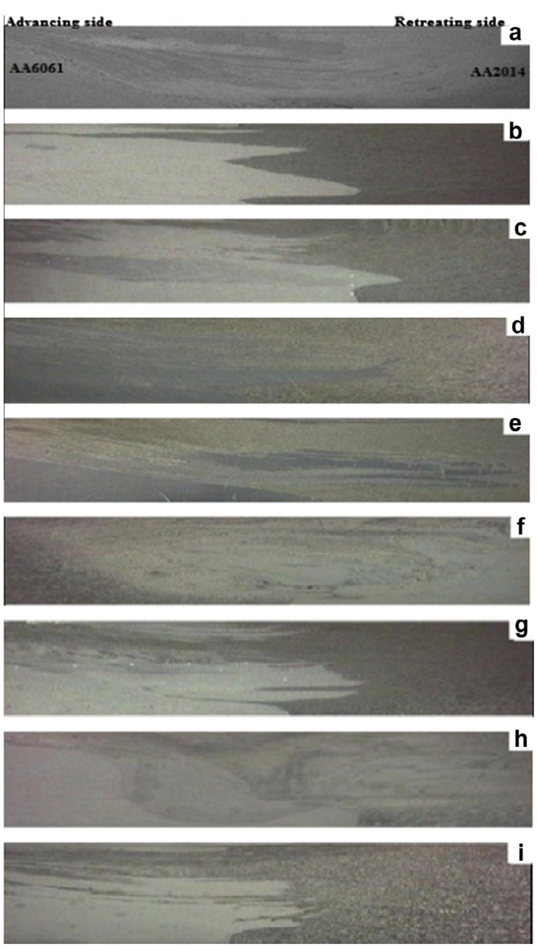

Fig. 13. Macrostructure of non heat treated welded blanks at different process parameters conditions: (a) TWB(900-16-0), (b) TWB(900-24-1), (c) TWB(900-32-2), (d) TWB(1150-16-1), (e) TWB(1150-24-2), (f) TWB(1150-32-0), (g) TWB(1400-16-2), (h) TWB(1400-24-0) and (i) TWB(1400-32-1).

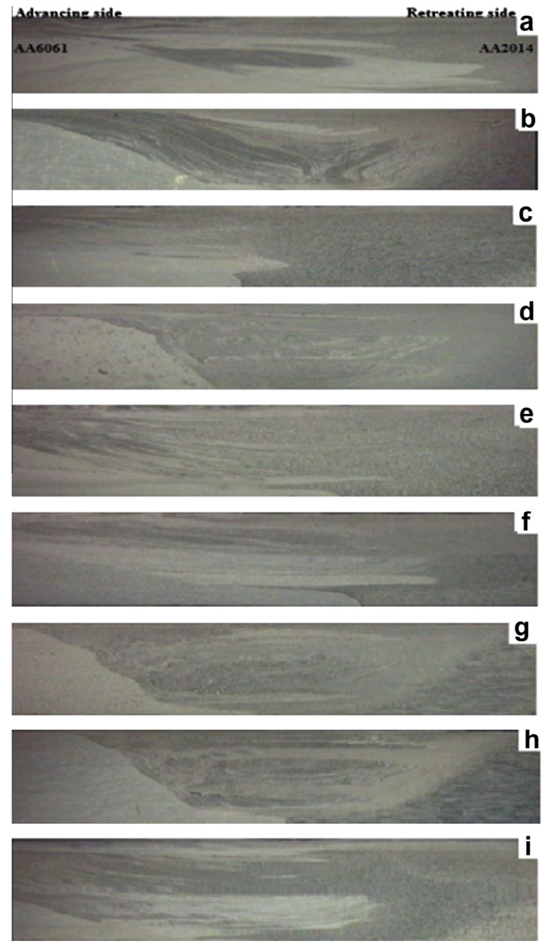

Fig. 14. Macrostructure of heat treated welded blanks at different process parameters conditions: (a) HTWB(900-16-0), (b) HTWB(900-24-1), (c) HTWB(900-32-2), (d) HTWB(1150-16-1), (e) HTWB(1150-24-2), (f) HTWB(1150-32-0), (g) HTWB(1400-16-2), (h) HTWB(1400-24-0), (i) HTWB(1400-32-1).

blanks at different welding conditions. The microstructures reveal that the mixing of the AA2014 and AA6061 alloy has taken place in all the welding conditions due to the stirring action. From Fig. 15d and e it was observed that, at 900 and 1150 rpm, a homogenous mixing of the constituents has taken place with fine grain size. The fine grain size is due to the refinement and dynamic recrystallization that has taken place due to a favourable rotational speed and welding speed. The dynamic should go hand in hand with the stirring that takes place during the welding process. However, at higher rpm (1400), proper mixing of the alloy has not taken place. Fig. 15f reveals that the alloy has been welded with patches of AA6061 and AA2014. This has resulted in lower formability. The higher rpm has failed to mix the alloying elements in a uniform manner and an uneven mixing of the alloys has taken place resulting in poor formability.

4. Conclusions

In the present work, friction stir welding was carried out on AA6061 to AA2014 aluminium alloys followed by LDH test. A non heat treated TWB made of AA6061 and AA2014 samples showed varied elongation values, resulting in poor formability. To achieve uniform elongation on either side of the TWB, solution treatment was done on AA2014 alloy. Formability tests were then done on the TWB made using the non heat treated AA6061 alloy and a heat treated AA2014 alloy. A uniform elongation on either

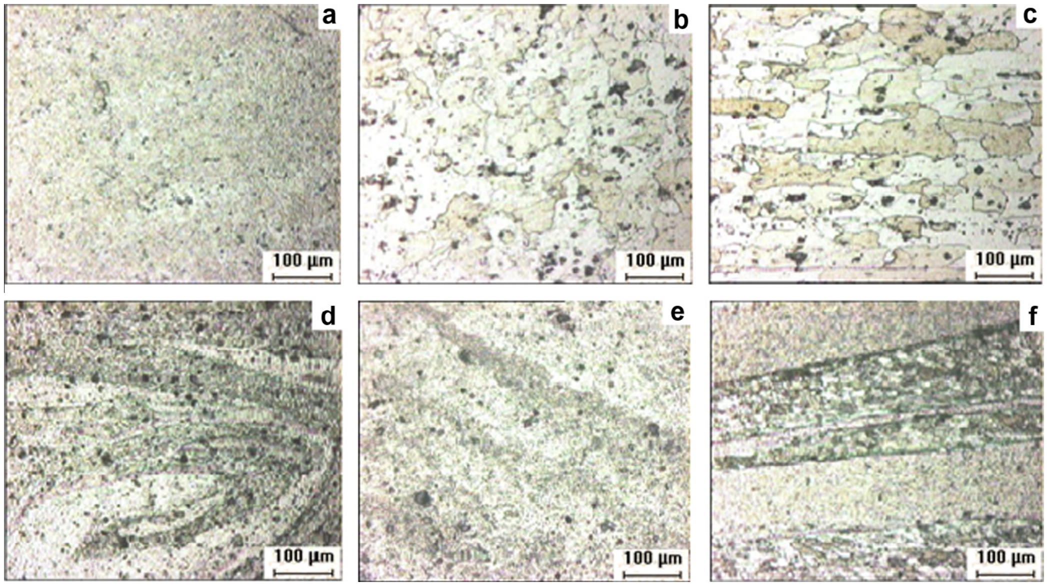

Fig. 15. Microstructures of welded zone of TWBs (a) base material – AA6061 (b) base material – AA2014 (c) Naturally aged AA2014 alloy (d) TWB at process condition of 900 rpm, 16 mm/min and 0° tool tilt angle (e) TWB at process condition of 1150 rpm, 16 mm/min and 1° tool tilt angle and (f) TWB at process condition of 1400 rpm, 32 mm/min and 1° tool tilt angle.

side of the TWB was achieved on a sample that was solution treated and tested after five days of natural aging. Thus the new methodology of giving a differential heat treatment to the samples has resulted in uniform elongation along the weld line with little or no weld line movement.

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