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ORIGINAL ARTICLE

Comparison of electromagnetic forming of friction stir-welded blanks of dissimilar material AA 5052-AA 6061 with conventional forming process

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Abstract In this work, studies on formability of Tailor Welded Blanks (TWB) were carried out by means of both quasi-static and high speed forming process. TWBs were manufactured as welded blanks of dissimilar material combination. Welding of AA 5052-H32 to AA 6061-T6 aluminium alloy of 1 mm thickness was done with the help a friction stir welding (FSW) process. Limit dome height (LDH) test was performed by both conventional hydraulic press forming (HPF) and by a high-speed forming process called electromagnetic forming (EMF) process, to investigate the forming behaviour of the TWB. Subsequently forming limit curves (FLCs) were plotted to quantify forming behaviour. Dome heights and FLCs of TWB and base materials are compared. Similar comparison has been made between conventional forming and EM forming process. It is found that the formability of TWB increases considerably with EMF process with base AA 5052 material showed largest increase in formability. Effect of weld line offset on the formability was also investigated. When the weld line was offset by 25 mm towards AA 6061 side of the TWB, the welded blanks showed maximum forming behaviour by EMF process in terms of both dome height and FLC.

Keywords Tailor welded blank · Friction stir welding · Electromagnetic forming · Limit dome height · AA 5052 · AA 6061

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1 Introduction

Modern vehicle construction opts for lightweight construction, better fuel consumption, and better crash worthiness with more emphasis on lesser energy and environmental impact during the manufacturing process. For this reasons, attention is being shifted from traditional material like steel to a lighter material like aluminium alloy. Aluminium alloys have higher strength to weight ratio but they attribute to lower formability and higher cost compared to steel. For aluminium alloys, advanced fabrication techniques like friction stir welding (FSW), electro hydro forming (EHF), and electromagnetic forming (EMF) are being used and investigated for better formability and for clean manufacturing. Further for material saving and structural rigidity aluminium alloys are used in the form of tailor welded blanks (TWBs).

Friction stir welding (FSW) is a solid-state welding process which is used for joining difficult to weld materials like aluminium and magnesium alloys [1]. In FSW process, a rotating tool is plunged in between the two work-pieces to be welded and the rotation of the tool creates excessive friction that heats up the interacting work piece materials to a plastic state and forges the material during stir action of the tool resulting in a solid phase bond joint. FSW consumes comparably lesser energy to the conventional welding process and it is environmentally friendly as there is no use of added flux and shield gas [2].

Aluminium tailor welded blanks (TWBs) consist of two or more different grade of sheet metals or of different thickness sheets that are welded together into a single blank. In the subsequent operation, these blanks are formed into different components of automotive and aerospace body. TWB of thin sheet of different grades aluminium alloys are widely used in automotive, aerospace and ship industries to take advantages of lightweight and structural stiffness [3].

The TWB of both 5xxx and 6xxx series aluminium alloys are good candidate for automobile industry. Generally, AA 5xxx series aluminium alloys are used as inner body panels with complicated shape as a rigid structural body parts since it develops undesirable visible surface defect but having better formability [4] while AA 6xxx- series are usually used as stamped parts for outer body panel [5].

FSW of dissimilar aluminium alloys between 5 xxx and 6xxx series have been studied by many researchers. Successful welding was obtained between AA 5083 and AA 6061 by Shigematsu et al. [6], AA 5182- AA 6016 by Giera et al. [7], AA 6061- AA 5052 by Hong et al. [8], Leito et al. [9], Park et al. [10] and Rajkumar et al. [11]. However, successful welding of aluminium thin sheets by FSW is quite difficult to obtain though few researchers have studied FSW of less than 2 mm thin sheets [7, 10, 12–14]. To obtain improved formability of aluminium alloys eventually which led to renewed interest in high velocity forming processes, one of them is electromagnetic forming (EMF). EMF is a high velocity forming process which utilizes magnetic pulse forces to deform the worksheet. This repelling pulse magnetic forces is generated by an intense opposing transient magnetic field between a current carrying copper coil tool and a conductive worksheet. During the process, a velocity of 100 m/s is easily achievable by the worksheet [15]. EM forming has been in use since the late 1950's [16]. Research on EM forming of sheet metal to explore the possibility of applying this process to automotive production has also been done. Yudaev et al. [17] studied EM forming of flanges and stiffeners with 1.5 mm aluminium sheet and reported forming limits that were higher compared to quasi-static forming. Balenethiram et al. [18] reported a hyperplastic behaviour of material with a high speed forming due to the effect called inertial ironing. Vohnout et al. [19] combined quasi-static process and EM forming and concluded that the combined process yielded increased formability compared to a quasi-static process. Oliveira et al. [20, 21] reported experiments and numerical analysis on free EM forming and die cavity fill of 1.0 and 1.6 mm sheet AA 5182 and AA 5754. Noh et al. [22] successfully achieved a desired shape by using two step EMF process involving the use of two coils and a middle-block die. Li et al.

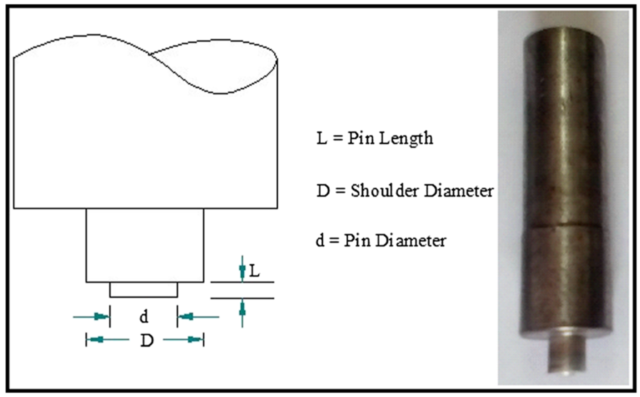


Fig. 1 FSW tool nomenclature and tool used in the present work

[23] analysed the formability of a low conductive metal sheet by electromagnetic forming process by employing a new method to generate data for the forming limit diagram. Recently, Cui et al. [24] found that for a given discharge, both the sheet thickness and current damping exponent plays an important role in achieving the optimum current frequency.

Forming behaviour of friction stir-welded blank is essential to study for its application in automobile and aerospace structures. There is no previous literature found on EM forming of Aluminium TWB, hence the purpose of the current work is to analyse and compare the forming behaviour of friction stir-welded (FSWed) TWB of aluminium alloy sheets between conventional hydraulic press forming (HPF) and EMF. To investigate the forming behaviour of TWBs by both the forming methods, limit dome height (LDH) tests were performed with each process and corresponding forming-limit curve (FLC) were compared. In this paper FSW of thin sheet (1 mm) of different grades of aluminium alloy namely AA 5052 H32 to AA 6061 T6 were done first and then high strain rate formability test were analysed with the help of EMF process.

2 Experimental procedures

2.1 FSW tooling and process parameters

Combination of thin sheets of AA 5052 H32 (pre-strain hardened) and AA 6061 T6 (tempered) of thickness 1 mm were friction stir welded keeping AA 6061 in advancing side.

Table 1 Nominal chemical composition of the base materials (wt%)

Alloy	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn	other
AA 5052- H32	95.7–97.7	0.15–0.35	Max 0.1	Max 0.4	2.2–2.8	Max 0.1	Max 0.25	Max 0.1	Max 0.15
AA 6061- T6	95.8–98.6	0.04–0.35	0.15–0.04	Max 0.7	0.8–1.2	Max 0.15	0.4–0.8	Max 0.25	Max 0.15

Table 2 Tooling and process parameters

Sl no.	Shoulder dia.(D) (mm)	Pin dia. (d) (mm)	Pin length (L) (mm)	Tool rotational speed (RPM)	Tool traverse speed (mm/min)
1	10	3.5	0.7	1500	68

The chemical compositions of each alloy is listed in Table 1. Each sheet with a dimension of 200 mm × 100 mm was butt welded in the rolling directions with a cylindrical stainless steel (SS)-H13 as a plunge tool as shown in Fig. 1. A mild steel plate of 25 mm thickness was used for backing plate.

After initial trial, optimum effective welding was obtained at tool traverse of 68 *mm/min*. The summary of tool and other process parameters for the welded blanks are given in Table 2.

2.2 Formability test setup

The formability of the FSW TWBs were evaluated in terms of both quasi-static and high speed forming and compared. For conventional method, hydraulic press forming (HPF) with punch was used to free form the blanks for limit dome height (LDH) test while for high speed forming, Electromagnetic forming (EMF) process was used. The conventional testing device comprises a 100 mm diameter hemispherical punch, a 108 mm diameter die, and a blank-holder as shown in Fig. 2. The fixture was built with AISI P20 tool steel for punch tool and cast iron for die and blank holder.

EMF is high strain rate forming process where an electrically superior conductive coil which produces EM field and Lorentz force, acts as a contactless punch to deform the work sheet. Working principal of EMF is based on Maxwell electromagnetism theory [25]. An extremely strong transient magnetic field generated due to primary current passed through the copper coil which in turn induces eddy currents in the aluminium alloy sheet and thus repulsive electromagnetic forces (Lorentz forces) generated causes the deformation of the sheet.

A schematic diagram of EMF system used in present experiment is shown in Fig. 3. A large amount of energy (up to 10 kJ) is stored in two large capacitors by charging to a high voltage (up to 15 *kV*). The stored energy in the capacitor bank can be represented by

$$E = \frac{1}{2} C V^2 \quad \text{(i)}$$

where E is the discharge energy, C is the total capacitance of the capacitor banks, and V is the initial charge voltage.

When the current is discharged from the capacitors to the coil, it takes the form of a damped sinusoidal wave and acts like a ringing Inductance-Resistance-Capacitance (LRC) circuit. The current, I, generated can be expressed by incorporating total circuit resistance and inductance values, which are represented by equivalent resistance, R, and equivalent inductance, L.

$$I = \frac{V}{\omega L} e^{\beta t} \sin \omega t \quad \text{(ii)}$$

Where, ω is current frequency and current damping exponent $= \frac{R}{2L}$. Finally, the electromagnetically generated Lorentz force, $\vec{F}$ between the tool-workpiece interference in terms of current density, $\vec{J}$ and magnetic flux density, $\vec{B}$ is given by

$$\vec{F} = \vec{J} \times \vec{B} \quad \text{(iii)}$$

experiments. The system has a maximum energy storage capacity of 10 kJ at 15 kV and it consists of two 45 μF capacitors each with a system inductance of 400 nH (Fig. 4).

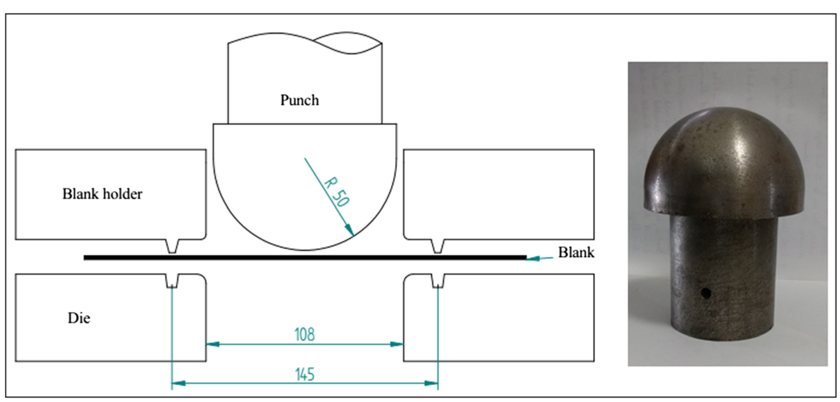


Fig. 2 Die and tool parameters for conventional LDH test with the image of actual punch used

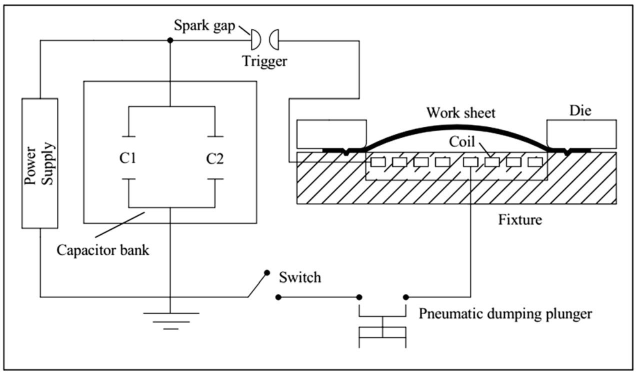


Fig. 3 Schematic circuit diagram of the EMF process

A six-turn spiral copper coil, as shown in Fig. 5, of 110 mm diameter was used. The free form die was bolted down to hold the blank in place and was of same dimension as that of conventional test setup. The cavity of the free-form die was open to the atmosphere eliminating the requirement to evacuate the die chamber. Grid circles of diameter 2.4 *mm* were marked on all TWBs prior EMF for Forming Limit Diagram (FLD) analysis.

3 Results and discussions

3.1 Mechanical properties of the welded blanks

3.1.1 Tensile properties

For tensile test, the friction stir-welded samples were cut according ASTM E8M standard specifications [26] and keeping the weld line in transverse direction.

The stress-strain graph of welded blank with base materials AA 5052 and AA 6061 are plotted in Fig. 6. It can be interpreted from the graph that AA 6061 has the highest ductility and toughness. Additionally, the elongation as well as strength of both the base materials are found to be higher than that of the friction stir-welded sample (Table 3). The tensile strength of FSWed blank is lower by about 41% from that of AA 6061 and 27% from that of AA 5052.

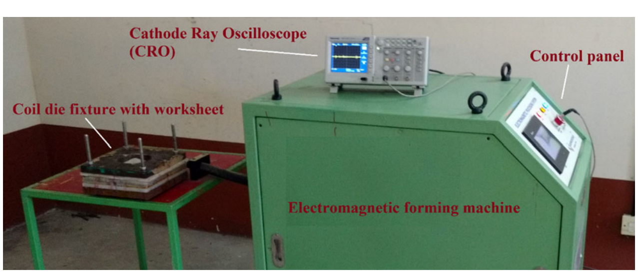


Fig. 4 Electromagnetic forming setup

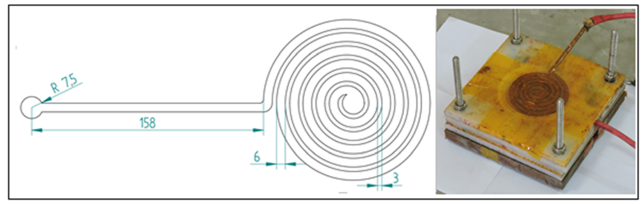


Fig. 5 Schematic diagram of the coil tool with the actual coil engrave in the fixture

The low hardness values at thermomechanical affected zone (TMAZ) on the weld region of AA 5052 side contributes to the low strength of TWB. Hence, strain localization takes place on this region which ultimately led to the fracture at welded joint during tensile testing of the FSW samples. The detailed hardness and microstructure study of the process was reported in Doley et al. [27].

3.2 Formability behaviour of TWBs

3.2.1 Limit dome height (LDH) test

To study the influence of weld line on the formability of TWB at high speed forming, LDH tests were carried out by EMF process. Two orientations were analysed, in one of the orientation weld line was moved by 25 mm towards AA 6061side and in another weld line was moved by 25 mm towards AA 5052 side. The sample numbering with weld orientations are illustrated in Fig. 7. In Fig. 8, all the dome heights of the TWBs with failure are plotted against different applied voltages. The maximum dome height reached by weld line centred sample 1 is 17.4 mm which is lower than that of sample 2. Moreover, sample 2 has the highest dome height prior failure among the three samples which is 19.1 mm while for sample 3 it is 12.2 mm. When weld line is offset towards AA 6061, more portion of AA 5052 cover up the copper coil for deformation which is

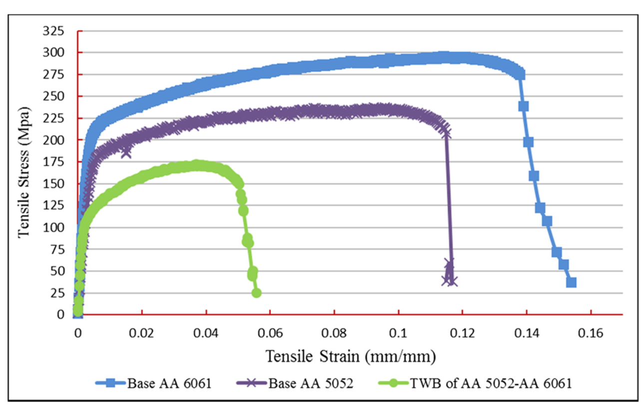


Fig. 6 Tensile Stress Vs Strain curves for base material AA 5052, AA 6061 and FSWed TWB sample

Table 3 Mechanical properties of base material and friction stir-welded samples

Material	Thickness (mm)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Modulus of elasticity (MPa)	Extension at break (mm)
6061 T6 (Base)	1	294.02	212.5	70,259.96	2.5
5052 H32 (Base)	1	235.33	175.7	51,869.37	2.87
5052–6061 (FSW)	1	172.4	114.6	75,986.33	1.44

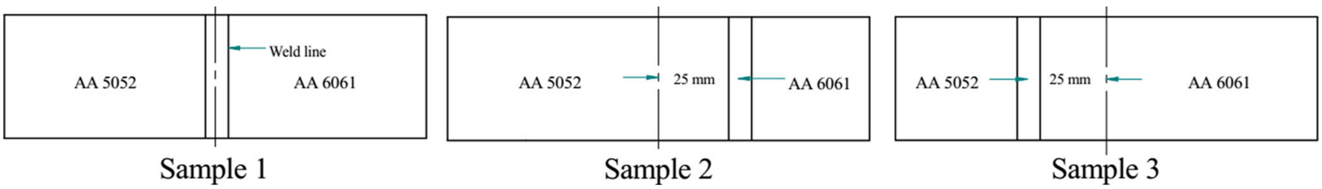


Fig. 7 Orientation of weld line of FSWed blanks

in favour for occurrence of more deformation. As AA 5052-H32 has better formability characteristics over AA 6061-T6 which can be seen from the results of tensile test and hardness test [27]. With a property of more stiffness and material hardness, AA 6061 is tougher to deform than AA 5052.

Figure 9 shows the graph of transient current flowing through the coil at highest discharge voltage. Current curves were acquired using Cathode Ray Oscilloscope (CRO) through Rogowski coil. The current frequency was found to be 14.88 kHz for the given coil tool. The cycle time was equal to 67.2 μs, so the maximum deformation in TWBs were expected to occurred at 16.8 μs.

The plotting of currents versus voltages for the EMF process is illustrated in Fig. 10. The change in peak current takes place due to change in mutual inductance of the circuit. Increase in peak current has been observed for increase in voltage. The highest current before failure for sample 2 was found to be 88.85 kA which was highest among all welded blanks. For samples 1 and 3, the measured current is approximately same which is about 82 kA.

LDH test is biaxial test causing stretching of the FSW sample both along and across the weld. So during the process, the softest of all region will experience larger deformation and finally failure. Figure 11 shows the final safely deformed samples and fractured samples with the region of failure which is at TMAZ of weld region. The initiation and occurring of cracks at the weld zone is random for the TWB samples as shown in Fig. 11d, e, and f. For sample 2, the crack is at TMAZ of AA 6061 side while for samples 1 and 3, it is on the middle of the weld zone.

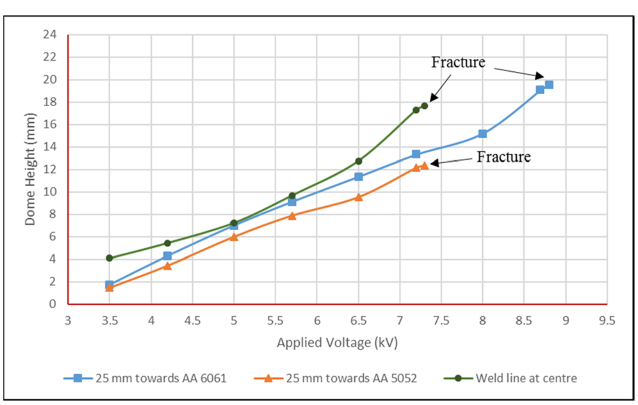


Fig. 8 Dome heights of weld line orientated samples obtained by EMF process

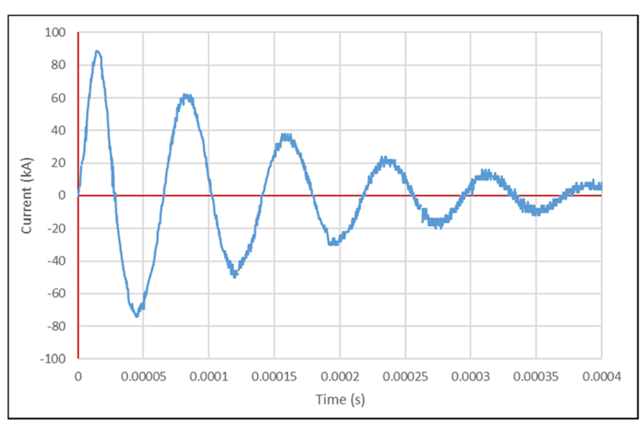


Fig. 9 Current variation over time at 8.7 kV

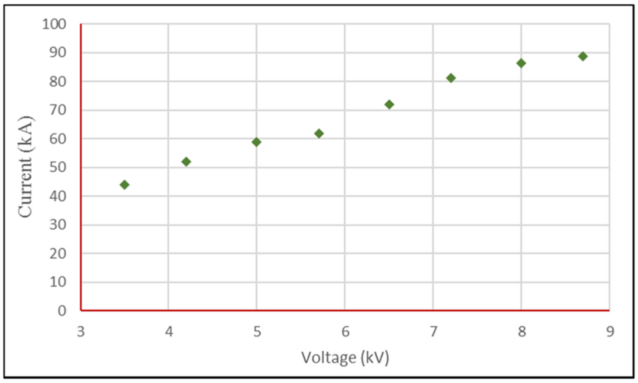


Fig. 10 Current variation over voltages

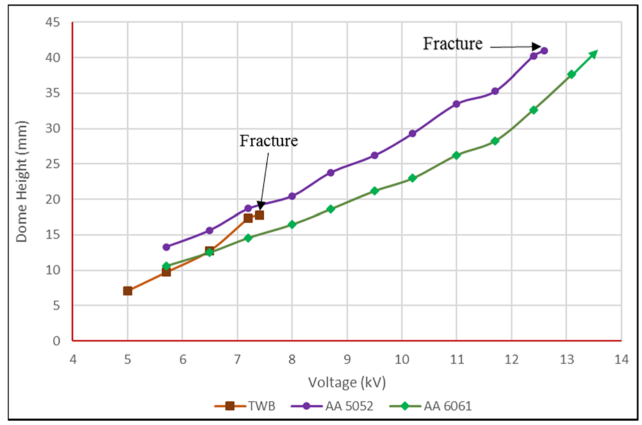


Fig. 12 Dome heights of TWB and base materials obtained over various voltages

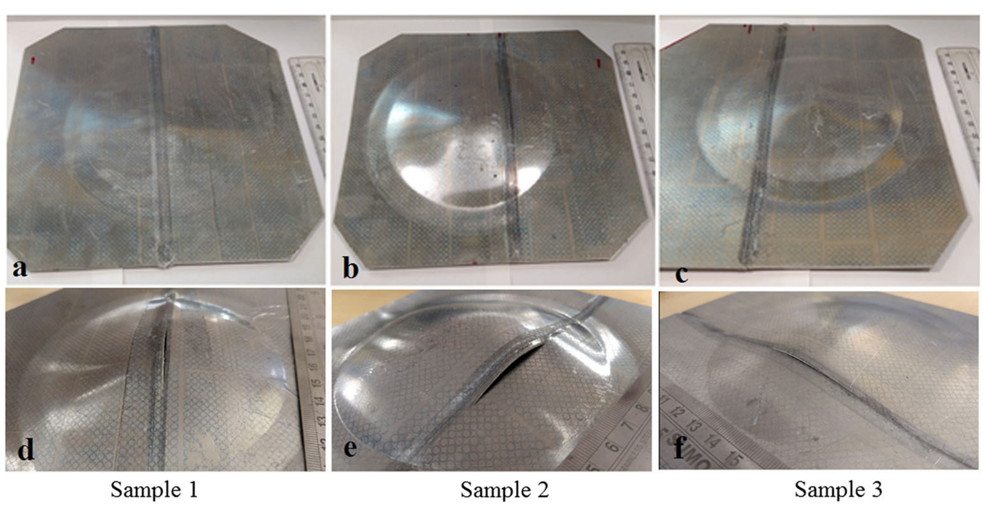
The dome heights of base 5052 are always found to be higher than that of base 6061 for corresponding applied voltages (Fig. 12). AA 5052 has lower ductility in tensile however it has greater formability characteristics over AA 6061, at both quasi-static and at high strain rate forming process. Maximum dome height attained by AA 5052 prior fracture is 40.95 mm at 12.4 kV. Due to capacity limitation in the present EMF system, base 6061 which has a greater hardness than AA 5052, could not be formed until fracture and the maximum height obtained without fracture for AA 6061 is 37.68 mm at 13.18 kV.

The LDH test shows significant difference for maximum dome heights between conventional and EMF process. There is a percentage increase of about 115% for base AA 5052 from conventional forming to EMF process while for AA 6062 it is about 83.4% increase as shown in Fig. 13. The increase in dome height for FSW blank is 42% by EMF as compared to HPF. The reason behind increase in formability by EMF is due to the inertia effect which upholds delay in necking and inertial ironing effect. The shape of the electromagnetically deformed samples shows a hump, as shown in Fig. 14, at the centre which is due to the inertia effect. The intense magnetic field which is characterized by the shape of the coil causes a heterogeneous distribution of strains at the worksheet and at high speed this brings the inertia effect to deforming sheet.

3.3 Forming limit diagram (FLD)

The experimental forming limit curves (FLCs) are plotted at border line of safe and failed grid circles and below the curve line lies all the safe grids. In case of welded samples, FLC for welded sample 2 is highest among sample 1 and sample 3 (Fig. 15). As expected, sample 2 with more ductility and dome height is showing higher FLC. However, there is no significant increase in major strains as the rise in FLCs is mainly due to the difference in minor strains. While for conventional and EMF process

Fig. 11 Final dome heights of offset samples formed by EMF where (**a**) is sample 1, (**b**) is sample 2 and (**c**) is sample 3 which are safely deformed while (**d**), (**e**) and (**f**) are fractured samples of 1, 2 and 3, respectively



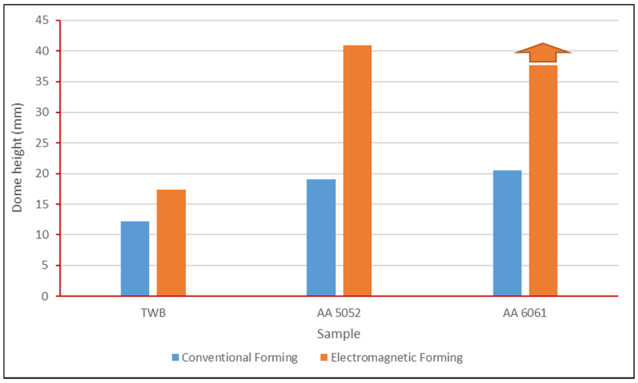


Fig. 13 LDH of base and TWB samples formed by conventional and EMF process

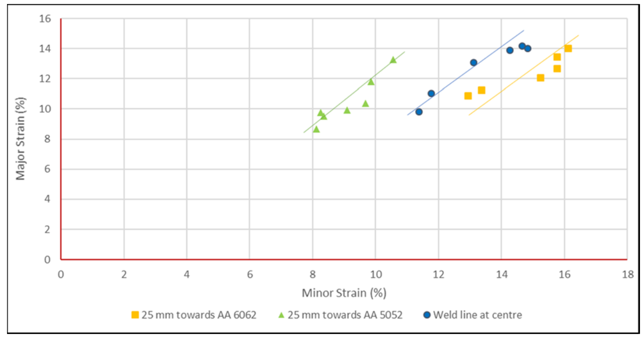


Fig. 15 FLD of different weld line orientated samples formed by EMF

the difference in FLCs of welded blanks is more pronounce in terms of both major and minor strains. In Fig. 16, FLC of Electromagnetically formed samples shows same shape with a higher FLC of about 18% more than that of FLC of conventionally formed samples. The uniform rise in FLC of alloys with EMF shows the proportional effect of strain rate sensitivity. At high velocity, forming is characterized by high strain rate, aluminium alloys are showing positive rate sensitivity. The FLCs of welded blanks with base materials formed by both processes are shown in Fig. 17. The FLC of base material 5052 shows an increase of about 89% by EMF process. AA 6062 being unable to deformed till fracture hence forming curve could not be obtained for the same. In the present study the curve of AA 5052 is highest when formed by EMF but it is lower than AA 6062 when formed by conventional forming process. This is consistence with forming results obtained with LDH test where AA 5052 attained maximum height with EMF process. The experiment shows significant improvement in formability of FSWed TWB of AA 5052 to AA6062 by EMF process with respect to quasi-static process.

4 Conclusions

Formability analysis was performed for welded aluminium blanks with conventional and high speed forming process. Combination of different grades of aluminium alloys specifically AA 5052-H32 (work-hardened non-heat-treatable) and AA 6061-T6 (heat-treatable) of 1 mm thickness each were welded together by Friction Stir Welding (FSW). The Tailor Welded Blanks (TWB) were then mechanically tested and compared with base materials. Formability evaluation was done in terms of limit dome height (LDH) test and forming

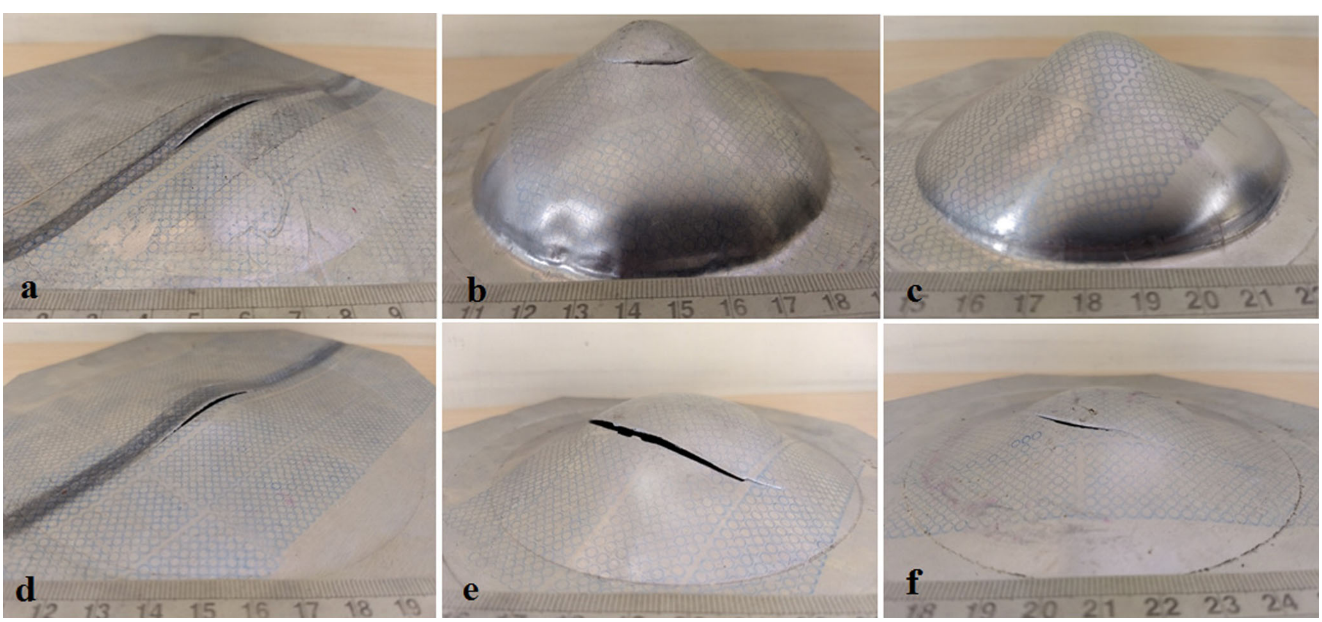


Fig. 14 Final fractured dome heights obtained by EMF process **a** TWB, **b** AA 5052, **c** AA 6061, by conventional HPF **d** TWB, **e** AA 5052 and **f** AA 6061

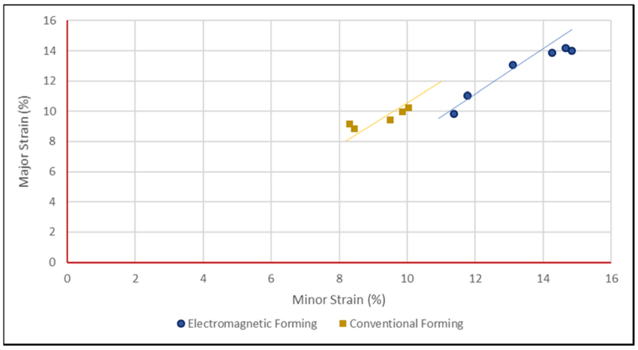


Fig. 16 FLD of FSWed samples formed by conventional and EMF process

limit diagram (FLD) with both conventional hydraulic press forming (HPF) and electromagnetic forming (EMF) processes for comparison. The main conclusions can be summarized as follows:

1. The tensile strength of FSWed blank is less than that of both base materials. It is lower by about 41% from that of AA 6061 and by 27% from that of AA 5052. During tensile test AA 6061 shows higher ductility and toughness.
2. Effect of weld line location when formed by EMF shows significant change in formability. Bulge test show more dome height can be achieved when weld line is offset by 25 mm towards AA 6062, which is due to higher formability of AA 5052 over AA 6061 at quasi-static as well as at high strain rate forming processes. Lowest height is obtained when weld was kept offset towards AA 5052 and intermediate height were obtained when formed at exactly with zero offset (at centre). This is also true with corresponding FLCs.
3. With EMF process, FSWed blank achieved a greater height compared to conventional process. The percentage increase is 42% with EMF process. Dome heights attained by FSWed blanks in both conventional and EMF process are lesser than that of the base materials. The percentage increase in dome heights by EMF over conventional process for base 5052 is 115%. Since base 6061 could not be deformed till fracture, relative percentage increase of AA 6061 could not be obtained; however, forming curve for conventional process shows AA 6061 has higher magnitude over AA 5052.

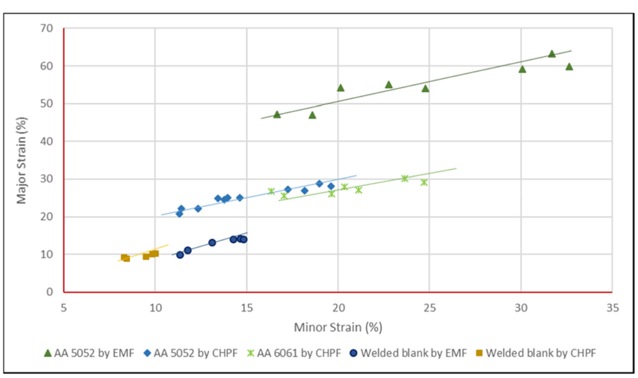


Fig. 17 FLD of base materials and FSWed samples formed by conventional and EMF process

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