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Investigation on the Influence of the Lubrication on the Formability of Dissimilar Tailor Welded Blanks

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Abstract In sheet metal forming, many variables influence the forming operation such as the base material properties, deformation rate, forming temperature, lubrication between the punch and blank etc. This study reports the effect of different lubricants on the formability of dissimilar welded aluminium blanks. The lubricants selected for the tests are liquid, semi solid and solid based. The strain distribution profile and the forming limits of the welded blanks were studied for each and every lubricant chosen. Of the three lubricants, the welded blanks coated with Teflon lubricant yields the better results by improving the forming limits and homogenised strain distribution compared to other lubricants.

Keywords Aluminium alloy · Friction stir welding · Lubrication · Limiting dome height · Forming limit diagram

1 Introduction

Aluminium alloys based Tailor Welded Blanks (TWBs) are used in automobile and aerospace industrial applications, where they need to minimize the weight in high strength parts. Researchers are involved in the making of TWBs of different aluminium alloys with good strength and formability. Friction Stir Welding (FSW) is a solid state metal welding technique and has proved as a successful welding method to make TWBs with better weld properties compared to fusion welding techniques. Jain et al. [1] have conducted deep drawing experiments to find the drawability of AA5754 and AA6111 aluminium alloys and concluded that 5754 alloy has better formability than 6111 alloy. Narayanasamy et al. [2] have studied the formability of HSLA and EDDQ steels and developed the strain distribution profiles of major strain and minor strains. A Forming limit diagram (FLD) is a diagram used to represent the safe, failure and critical deformation of the formed blanks [3]. These FLDs has been proved as an important and efficient tool to study the formability of aluminium blanks in different strain conditions and many researchers are working on FLDs around the globe. The information provided by the FLDs is very much useful for the designers and manufacturers. The FLD concept was first developed by Keeler [4] from the biaxial stretch tests. The critical ratio of major to minor strains produces the rupture on the blank. Later Goodwin [5] added to Keeler's concept by stretching the blanks to different stress conditions to develop negative minor strains resulting in the evolution of FLDs. Hecker [6] developed a standard approach by using different blank widths, which develops different strains with the help of limiting dome height test. In the past research, many theoretical predictions of failure of blanks have been carried in the metal forming operations [7, 8]. Some researchers have analysed the formability of welded blanks with the help of finite element analysis [9, 10]. Murat Dilmec et al. [11] have developed the FLD of AA2024 aluminium alloy and revealed that the Forming limit curve (FLC) level increases with increase in blank thickness. Many parameters influences the FLD of forming operations such as material behaviour, blank thickness, lubrication, forming equipment etc. [3, 12, 13]. In the forming operations, lubrication is typically used between

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the tools and blanks to reduce the friction and to improve the blanks formability. The use of lubrication allows contact pressure of punch more uniformly distributed and also helps to improve the surface quality of formed blanks [14]. It has been observed from the available literature that very limited works have been performed on the influence of lubricants on formability [14–16]. In this present investigation, the development of strain distribution profiles and forming limit diagram of the dissimilar welded blanks by the use of limiting dome height test have been reported.

2 Experimental Procedure

The base materials used were rolled aluminium alloy blanks of AA6061 and AA2014 of 3 mm thickness. The chemical compositions of the blanks are presented in Table 1. The mechanical properties of the base materials are shown in Table 2. AA6061 alloy has moderate strength and good formability and AA2014 has high strength and lower formability. Tensile tests were performed on the base material blanks to obtain the standard tensile properties such as tensile strength, yield strength, percentage of elongation, strain hardening coefficient (n) and strength coefficient (K). Tensile test specimens were prepared as per American Society for Testing and Materials (ASTM E8M) standard guidelines. The test was performed on universal testing machine and the tensile load was applied until fracture occurs in the specimen. The data acquisition system was used to collect the load and elongation values of the test specimen and present it in the form of nominal stress–strain curve. Then, this stress–strain curve is converted into true stress-true strain curve. The strain hardening behaviour of the base materials can be described by using the Hollomon’s equation.

$$\sigma = K\,\varepsilon^{n} \tag{1}$$

whereas σ = true stress (MPa), ε = true strain, n = strain hardening component, K = strength coefficient (MPa). Both strain hardening coefficient (n) and strength coefficient (K) values were calculated by using the log–log plot of the true stress-true strain curve.

Friction stir welding was performed with the fixed process parameters such as tool rotational speed of 900 rpm, welding speed of 24 mm/min and tool tilt angle of 1°. After welding, the blank samples were sliced from the welded blanks for LDH test. The sliced blanks were subjected to different state of strains such as tension–tension, plane strain and tension–compression on blanks of length 100 mm and varying widths from 20 to 100 mm. Circles of diameter 2.5 mm were marked on the blanks by electrochemical etching process to study the strains from the deformed circles after forming. The strains measured will be developed into formability limits. A total of three lubricants namely lubricating oil, MoS_2-grease and Teflon sheet were used and these are classified as liquid, semi solid and solid lubricant types. LDH test was used to evaluate the formability of the TWB. A hemispherical punch of diameter 36 mm was used to stretch the blanks up to its fracture. The test was first carried out without the application of lubrication and thereafter, the tests were carried out with the application of lubricants. Schematic diagram of LDH test is shown in Fig. 1 and the assembly of dies and punch used in the test is shown in Fig. 2. A 50 ton hydraulic press was used to form the welded blanks and it was operated at a punch speed of 0.3 mm/sec. The punch load was stopped immediately after the initiation of the fracture and when a sudden fall of the load was observed in the data logger during the forming operation. The punch load and dome height data were recorded and stored in digital data acquisition logger which was connected to the hydraulic press. The major strains at different points from the pole (weld line) were measured and strain distribution profiles were drawn by plotting the points from the pole in abscissa and the corresponding major strains (ε_1) on the ordinate.

In order to analyze the formability of TWBs, the deformed circles in necking region of formed blank were

Table 1 Chemical composition of base materials

Base material	Mg	Si	Cu	Ti	Cr	Al
AA6061	0.60	0.76	0.025	0.017	0.043	Balance
AA2014	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)	Elongation (%)	Strain hardening coefficient (n)	Strength coefficient K (MPa)
AA6061	198	273	22	0.23	468
AA2014	402	454	12	0.12	616

measured as major diameter and minor diameter with a tool maker's microscope. The major strain (ε_1) and minor strain (ε_2) were calculated by comparing with the original diameter of the circle. Finally, FLD curve was drawn by plotting the minor strain (ε_2) along the abscissa and the corresponding major strain (ε_1) along the ordinate, which separates the safe region from the unsafe region *i.e.* upper side of curve represents the unsafe strain region and lower side represents the safe strain region. It is well known that the left hand side of FLD represents the tension–compression region, right hand side represents the tension–tension region and zero minor strain represents the plane strain condition of the welded blanks.

3 Results and Discussions

From the LDH test results, analysis was made to evaluate the effectiveness of different lubricants on the formability

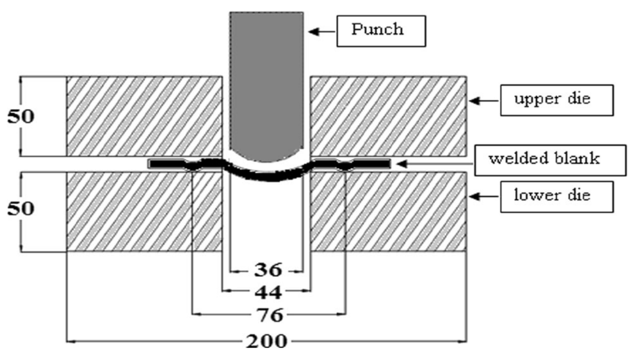


Fig. 1 Schematic diagram of LDH test

Fig. 2 Assembly of dies and punch used in LDH test

of dissimilar welded blanks. The LDH of welded blanks with and without lubrication are shown in Fig. 3. The rupture occurred between the welded blanks and the punch pole. The deformation is more on AA6061 blank side compared to AA2014 alloy side. The fracture occurred on the AA2014 alloy side of the welded blanks. This is due to the high ductility and high strain hardening coefficient value 'n' of the AA6061 blanks than the low ductile AA2014. It is well known that the stretchability of blanks is strongly influenced by strain hardening coefficient, 'n' and the formability is better for the blank with high 'n' value [17, 18]. No considerable improvement in the formability was observed in case of oil lubrication. Similar kind of results was reported by Luiz Mauricio et al. [14]. A small improvement has been observed with the application of MoS_2-grease lubrication. In these two cases, the lubricants have broken down during forming, exposing the contact between punch and the blank surfaces resulting in the premature rupture of welded blanks. Among the formed welded blanks, the LDH was highest (16.2 mm) when the Teflon sheet was used as a lubricant, due to less frictional conditions existing between the punch and welded blank surface. However, oil and grease lubricants did not show the same performance as the solid lubrication. Deformed welded blanks without and with Teflon lubrication are shown in Figs. 4a and b respectively.

Figure 5 shows the difference in punch load progression curves for welded blanks without and with lubrication. Punch load carrying capacity was almost same for welded blanks with oil lubrication and without lubrication. With the use of MoS_2-grease lubrication, a small increase in the dome height was observed and the load carrying capacity was little higher than the oil and without lubrication condition but lower than the Teflon sheet lubrication. In the case of Teflon sheet, the lubrication between the punch and the welded blank decreases the friction and increases the dome height. At any constant punch depth, the punch load required to deform the welded blank was lower, whereas the peak punch load increased with this lubrication. The

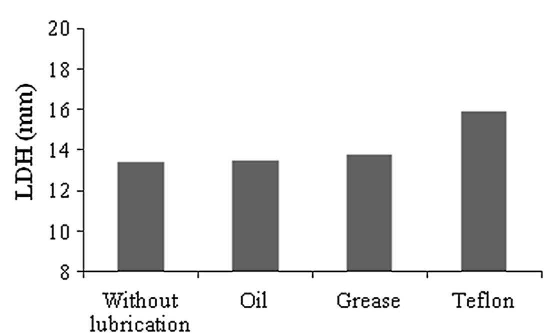
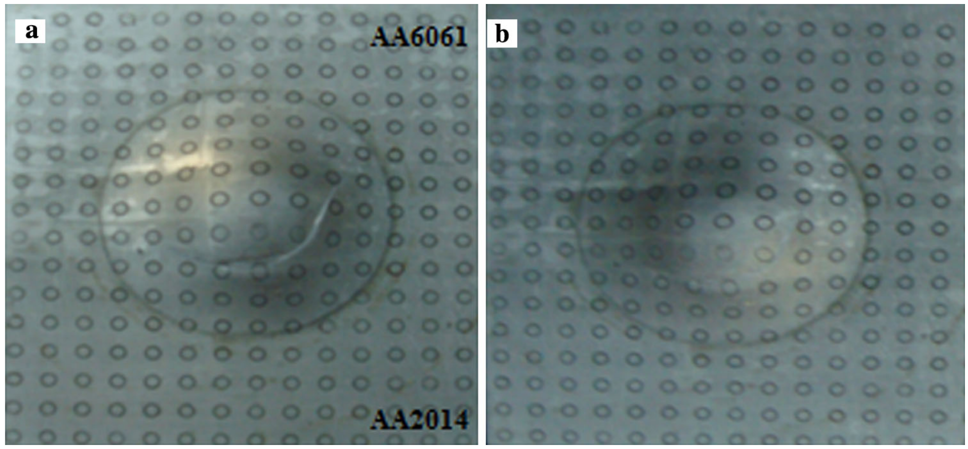


Fig. 3 Comparison of LDH for welded blanks with and without lubricants

Fig. 4 Formed welded blanks of **a** Without lubrication **b** Teflon sheet lubrication



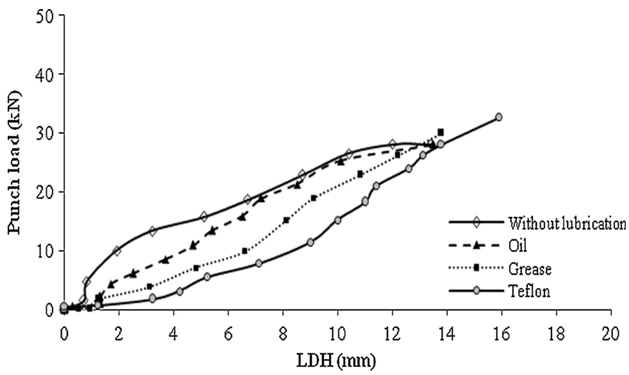


Fig. 5 Punch load-LDH curves obtained in the forming test with and without lubrication

reason is the reduction in the friction between punch and welded blank during the deformation. The above observations matches the results obtained by other researcher [16].

Figures 6a and b show the SEM microstructure of the two base materials. AA6061 alloy consists of Al, Fe, Mn, particles and some Mg_2Si precipitates in the dark colour. AA2014 alloy holds some $CuAl_2$ particles (white) in a solid solution matrix and some insoluble Fe, Mn, Si, Al particles. Figure 6c shows cross sectional microstructure of the stir zone, consisting of fine and uniformly distributed grains, formed by the stirring action of rotational tool during welding. Similar results were observed by other researchers [19, 20].

The measured major strains (ε_1) from deformed welded blanks were plotted for strain distribution profile with the points from the pole (weld line) of the dome surface. Figure 7 shows the measurement of the major strains on the dome surface of the welded blank along the centerline. It can be observed that there are two strain peaks on either side of the weld line. AA6061 alloy side of welded blank deformed more compared to the 2014 alloy side, due to the difference in mechanical properties of the two blanks. For the welded blanks without lubrication, the peak major strain on AA6061 side (0.1508) is higher than that on the AA2014 side (0.1204). However, less deformation occurred at the pole with a major strain value of 0.083. This is due to the high friction existing between the punch and the welded blank and also due to low ductility of the weld. These results are matching with result observed by

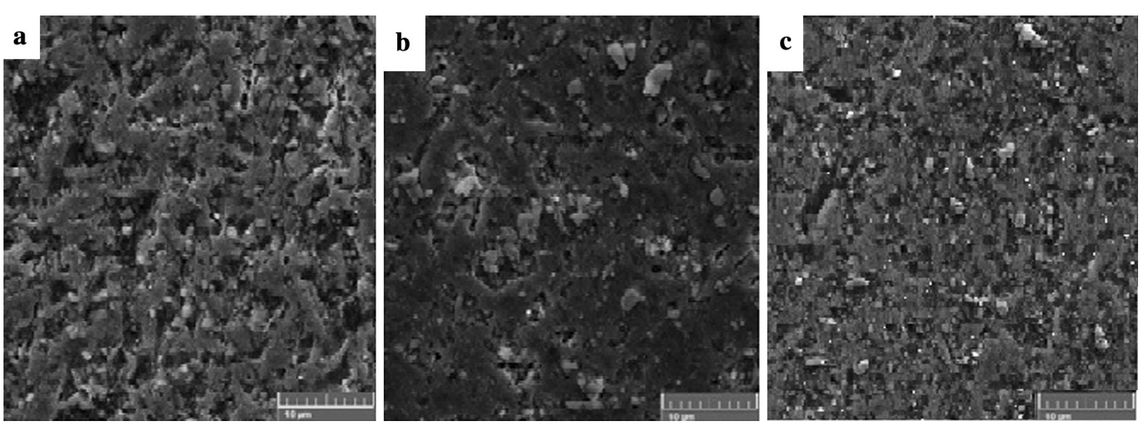


Fig. 6 SEM micrographs for **a** AA6061, **b** AA2014 base materials and **c** Stir zone of welded blank

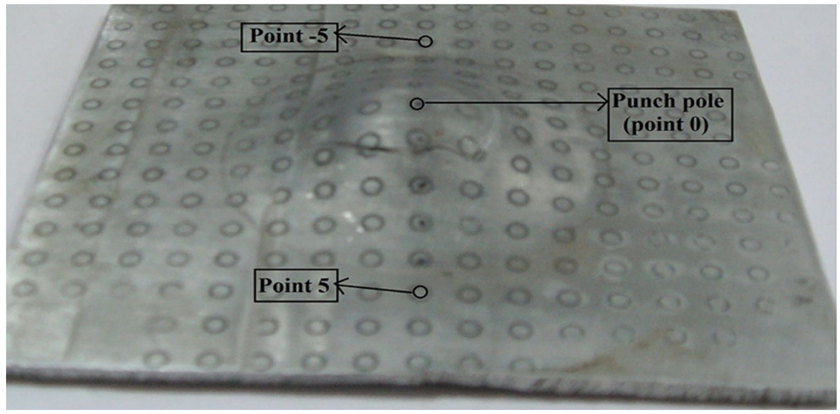


Fig. 7 Measurement of major strain values of deformed welded blank along centre line and perpendicular to the weld

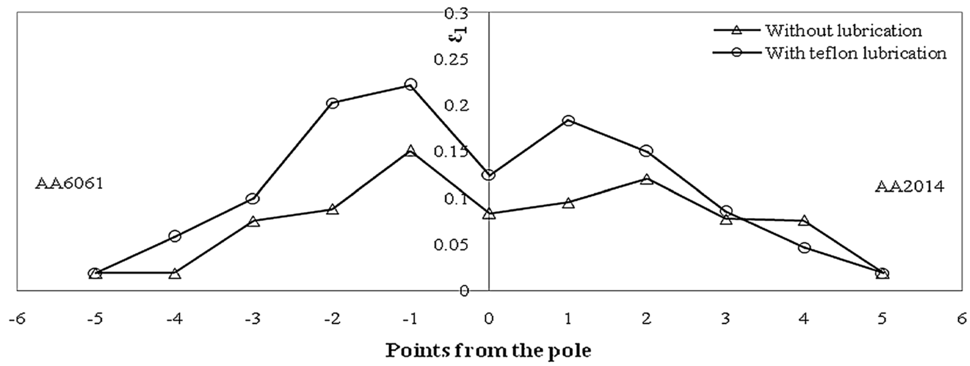


Fig. 8 The strain distribution profile on the dome surface for with and without the Teflon sheet lubrication

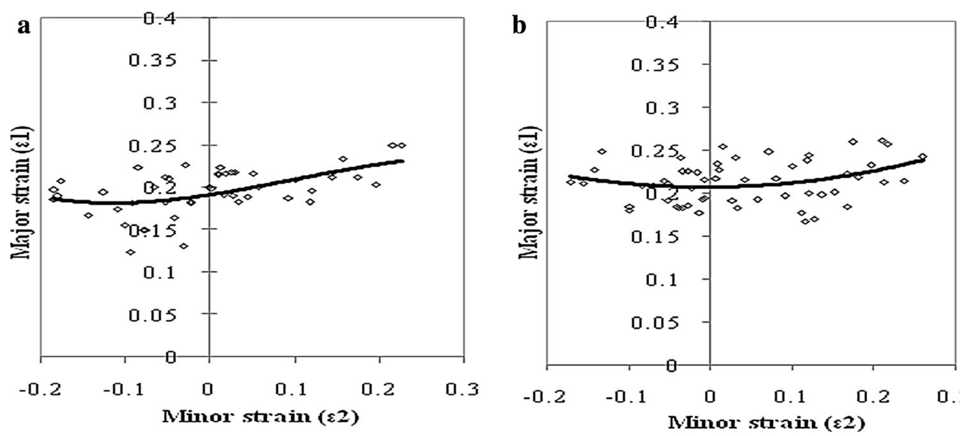


Fig. 9 FLDs of welded blanks for **a** Without lubrication and **b** with Teflon sheet lubrication

Sushanta Kumar Panda and Ravi Kumar [16]. Figure 8 shows the strain distribution profile across the weld on the dome surface of the formed welded blanks without and with the application of Teflon sheet lubrication. The applied solid lubrication between the punch and welded blanks reduces the friction and allows the welded blank slide easily on the punch surface. AA6061 alloy has high ductility and this reflects on the formed welded blanks in Teflon lubrication condition. A significant amount of deformation was observed at the weld center (pole) i.e. major strain is 0.1245; it was more when compared to without lubrication. On the other hand, the peak strain on AA6061 alloy side was 0.2216 and peak strain on AA2014 side was 0.1833. This strain distribution profile indicates that less strain gradients have occurred and hence more uniform strain distribution on the dome surface with Teflon sheet lubrication is experienced.

Based on the deformed circles on the necking zone, the major strain (ε_1) and minor strains (ε_2) were obtained. The forming limits of welded blanks were constructed for without lubrication and with the Teflon sheet lubrication condition as shown in Fig. 9a and b respectively. For the welded blanks without lubrication, the maximum major strain is about 0.231 in the tension–tension region and maximum major strain is about 0.187 for tension–compression region. In plane strain condition, the limiting major strain is about 0.192. For the welded blanks with Teflon sheet lubrication, the maximum major strain is about 0.240 in the tension–tension region and maximum major strain is about 0.220 for tension–compression region. In plane strain condition, the limiting major strain is about 0.207. It can be concluded that there is an improvement in the forming limits in all strain conditions of welded blanks with solid lubrication.

4 Conclusions

From the present study, it is observed that the application of lubrication between the punch and the welded blank has an effect on the formability of dissimilar welded blanks. Limiting dome height of welded blanks without lubrication is lower when compared to the LDH of welded blanks with lubrication. With the application of Teflon sheet lubrication, the LDH increased by 19 % with respect to the LDH obtained in forming without lubrication. Both sides of welded blanks were deformed to a larger extent and more uniform distribution was observed. It can also be observed that a higher limiting major strain of 0.207 was achieved in the forming limit diagram with the application of Teflon sheet lubricant.

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