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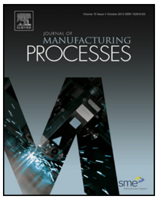

Full Length Article

Improvement in limiting drawing ratio of aluminum tailored friction stir welded blanks using modified conical tractrix die

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ABSTRACT

In the present work, aluminum tailor friction stir welded blanks (TFSWBs) of dissimilar grade and gauge combinations were fabricated successfully with optimized parameters. The tensile tests of TFSWBs were conducted perpendicular to the weld orientation to confirm the weld quality, and it was found that the failure occurred in the weaker base metal side. Subsequently, the limiting drawing ratios (LDR) of the base metals as well as TFSWBs were evaluated and compared using a conventional cylindrical die (CCD) and a modified conical tractrix die (MCTD) setup. Approximately, 27% and 14% improvements in LDR were recorded respectively for the dissimilar grade and the dissimilar gauge TFSWBs while using the MCTD setup. The finite element (FE) simulations of the improvements in LDR were carried out using LS-DYNA solver. For identifying the failure steps, the thickness true strain gradient (TTSG) method was incorporated successfully in the FE model. The predicted LDR and thickness distribution of the deep drawn cups of TFSWBs and the base metals were validated with the experimental data. Also, the strain envelope progression profiles and thinning development predicted from the validated FE models were analyzed rigorously to get an insight into the improvement in the material flow during deep drawing operation using MCTD.

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1. Introduction

Since more than one and a half decades, the automotive industries have been looking for the application of aluminum tailor friction stir welded blanks (TFSWBs) in vehicle components such as floor, door, and side panels. This is because of the higher strength-to-weight ratio of medium strength aluminum alloys (e.g., 5XXX and 6XXX series) than the automotive grade steels (e.g., interstitial free and extra-deep drawing). It can be found from literatures that, friction stir welding (FSW) can produce the promising quality of welds while tailoring dissimilar materials (grades) and thicknesses (gauges) of the aluminum alloys [1,2]. The solid state nature of FSW is obviously a potential reason for getting the reliable welds in aluminum alloys due to the absence of various fusion welding related defects such as gas porosity, segregation of alloys, hot cracking and dendrite formation. The FSW is energy efficient and environment friendly green process, and it can be automated implementing CNC technology for improving consistency and process efficiency along with mass production of TFSWBs. Additionally, the use of FSW causes less softening at heat affected zones (HAZs) and produces very fine equiaxed grains in the central stirred zone which is also referred as dynamically recrystallized zone (DXZ) [3]. As the major FSW region is contributed by DXZ, so the fine equiaxed grains of this region results in a reasonably good mechanical and metallurgical properties of the weldment [4,5]. However, the unsymmetrical material flow about the weld center and the misorientation of grains at the thermo-mechanically affected zones (TMAZs) in FSW cause the properties of TMAZs to be different on either side [3,4]. These make the properties of the weld region be non-homogeneous and introduce challenges in the post-weld forming performances of the blanks. Further, the formation of flash on the retreating side lead to mismatch in thickness across the weld, and this may pose some more challenges during the subsequent forming process. Therefore, the fabrication of aluminum tailor friction stir welded blanks (TFSWBs) followed by the formability examination is an important laboratory test which needs to be performed prior to the implementation in auto-bodies.

Sato et al. [6] measured the fracture limit strains of various TFWBs of AA5052 alloys by conducting test only in plane strain

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Abbreviations: TFSWBs, tailor friction stir welded blanks; CCD, conventional cylindrical die; MCTD, modified conical tractrix die; LDR, limiting drawing ratio; TTSG, thickness true strain gradient; AS, advancing side; RS, retreating side; YS, yield strength; UTS, ultimate tensile strength.

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deformation mode, and it was observed that the limiting strain increased with increasing grain size up to 10 μm and beyond this grain size the limiting strain decreased. Buffa et al. [7] considered that the heat flux across the weld center should be symmetrical to have homogeneous weld properties at both sides while welding similar and dissimilar gauges aluminum alloys. The FSW tool was offset towards the thinner base metal sheet with tool axis simultaneously tilted towards the thinner side in order to achieve symmetrical weld properties. It was observed that the tool offset is not effective for higher thickness ratio combination welds, and it caused a significant reduction in the joint strength. However, it was found that the spindle tilt towards the tool trailing edge apart from the inclination towards the thinner sheet side improve the joint strength. Also, several research studies are available to understand the effect of tool design and process parameters affecting the quality of the weld during FSW of different grade and gauge. Hence, optimization of FSW process is a crucial step to improve the joint strength both by experimentation and numerical simulation. In this context although huge literatures exist, however the experimental research work of Balasubramanian [8], Rodrigues et al. [9], Hirata et al. [10], Arora et al. [11], Eslami et al. [12], Hamdollahzadeh et al. [13], Sabari et al. [14], Teimurnezhad et al. [15] and the numerical modeling work of Reynolds et al. [16], Zhang and Zhang [17], Shi and Wu [18], and Taysom et al. [19] are worth mentioning. Further, the maximum formability can be achieved during post-weld forming if the TFSWBs are fabricated using the optimized FSW process parameters. Lakshminarayanan and Balasubramanian [20], Arora et al. [21], Nourani et al. [22], and Koilraj et al. [23] have worked to optimize the FSW process of different thin sheet materials to achieve the optimum weld strength and ductility. The earlier researchers had used different methods namely limiting dome height (LDH), drawability, and bending tests to determine the formability of aluminum TFSWBs. However, it is always preferable to conduct the transverse uniaxial tensile test before carrying out any formability test. It can reveal the weaker locations prone to failure and/or the defective welds [7]. Miles et al. [24–26] and Hirata et al. [27] used LDH test to evaluate the formability. Rao and Narayanan [28] carried out bending test to investigate the bendability and springback. Similarly, Rodrigues et al. [29] and Kim et al. [30] examined the drawability behavior of Al TFSWBs. Silva et al. [31] performed single point incremental forming to investigate the forming performance of AA1050 TFSWBs, and reported that the FSW was promising in the manufacture of complex sheet metal parts with high depths. Abdullah et al. [32] evaluated the drawability of AA1050 TFSWBs of different thickness combinations. It was observed that the maximum thinning appeared at the bottom corner of the cup in the thinner side of the drawn cups. However, the determination of limiting drawing ratio (LDR) which is very important measure of formability in a deep drawing process is rarely available in the open literature. The numerical and finite element analyses are important methods while selecting sheet forming process design and materials in automotive industries, as it saves fabrication of tools, materials, trial experiments and a great amount of time. Therefore, the modeling of TFSWBs and the subsequent formability assessment have also been reported by FE analysis, such as the work of Padmanabhan et al. [33], Lee et al. [34], and Zadpoor et al. [35].

It was noticed that the earlier researchers had mostly worked on the stretch forming behavior of the TFSWBs. Only a few research work [29,30] had been carried out on the deep drawing process. In fact, aluminum alloy AA5754 and AA5052 are mostly used for fabricating automotive parts such as fuel tank, floor panel, side and inner panels etc., by deep drawing [2,36]. There is no open literature available on weldability of the above mentioned aluminum grade while fabrication of TFSWBs. These lacunae in the literature motivated the present work, which is focused on the fabrication of two different aluminum TFSWBs: dissimilar grade combination using AA5052-H32 and AA5754-H22 of similar thickness of 2.0 mm, and dissimilar gauge combination using AA5754-H22 sheets of thicknesses of 2.0 mm and 2.5 mm. Subsequently, the formability of these two different TFSWBs was investigated. It was reported that the use of tractrix die had improved the LDR of monolithic sheet metal. The application of conical and tractrix dies eliminated the use of blank holder. Also, the blank was making line contact with the tractrix die profile during deep drawing. Hence, the friction force acting on the blank reduced. This resulted in easier material flow to the die cavity with mitigation of punch load and radial tensile stress in the cup wall [37]. Few research studies were available on forming behavior using tractrix die [38,39], and mostly severe wrinkling failure mode was reported while the thin sheet was flowing over the die profile. The material, which was drawn into the die cavity, was further reduced in diameter during the deformation. Eventually the material in the wall was collapsed into wrinkles due to the induced circumferential compressive stress. This restricted the improvement in LDR depending on the sheet metal thickness [40]. It was also previously reported by Havranek [37] that materials of higher plastic normal anisotropy ($\bar{r}$ -value) resisted more against wrinkling. The material with a greater $\bar{r}$ -value mitigates the compressive stress in the cup wall in contact with the die profile. Hence, the tendency of the wrinkling was reduced with the increase of the plastic normal anisotropy value.

There were no open literature on evaluation of LDR of a tailor friction stir welded blanks (TFSWBs) using tractrix die. It is imperative to estimate the improvement in forming behavior of the TFSWBs in terms of LDR and to study the role of mismatch in properties and thickness across the weldment. Hence formability of two different TFSWBs was investigated after designing a modified conical tractrix die (MCTD). Finite element modeling (FEM) was carried out and the results were validated with the experimental LDR and thickness distribution data. Thickness true strain gradient (TTSG) based damage criterion was also proposed and successfully implemented as a failure criterion in FE simulation. Subsequently, the strain evolution profile and thinning development of the validated FE model was analyzed to compare the material flow behavior using conventional cylindrical die (CCD) and MCTD setups during deep drawing process. This weldability and the subsequent formability data will be very much useful to engineers and researchers in the fabrication of aluminum TFSWBs for light weight automotive applications.

2. Materials and methods

The aluminum alloy sheets of 2.0 mm thick AA5052-H32 and both 2.0 and 2.5 mm thick AA5754-H22 were used in the present work due to their significant applications in the automotive sector, particularly in the structural inner panel [41]. Sub-size uniaxial tensile test specimens (as per ASTM E8/E8 M guidelines [42]) were prepared and tested in a universal testing machine (Instron, 8862) with a constant cross-head speed of 2 mm/min to determine various mechanical properties such as 0.2% yield strength (YS), ultimate tensile strength (UTS), total elongation till fracture (pct. elongation), strain hardening exponent (n-value), and strength coefficient (K-value). The material properties of the base materials are elaborately discussed in the subsection 3.1.1. The Lankford anisotropy ratio (r -value) was evaluated along three different orientations, viz. 0°, 45°, and 90° to the sheet rolling direction as per ASTM E517 standard [43]. Therefore, the specimens were stretched up to 70% of longitudinal true strain corresponding to UTS of the respective base materials. Finally, the r -value was determined by measuring the final width and length of the deformed specimens, and using

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