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OPTIMIZATION OF FORMABILITY OF TAILOR-WELDED BLANKS

OPTIMIZACIJA OBLIKOVANJA PRILAGOJENIH VARJENIH SUROVCEV

Valarmathi Guruvu[1], Ramanathan Kalimuthu[1], Sathiya Narayanan Chinnaiyan[2], Kathiresan Marimuthu[3]

[1]Alagappa Chettiar College of Engineering & Technology, Department of Mechanical Engineering, Karaikudi – 630004, Tamilnadu, India
[2]National Institute of Technology, Department of Production Engineering, Tiruchirappalli – 620015, Tamilnadu, India
[3]Thiagarajar College of Engineering, Department of Mechanical Engineering, Madurai – 625015, Tamilnadu, India
umkathir@gmail.com

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Nowadays tailor-welded blanks (TWBs) are used in the automotive industries to meet economic concerns, government regulations and design of vehicles with reduced weight and allow cost reduction. This technique is also employed while improving structural integrity and crash performance. Due to the raising environmental concerns about automotive emissions and the scarcity of natural resources, we need to reduce vehicle weight and improve fuel economy. As a result, the automotive industries employ TWBs. In this work, three grades of aluminum sheets (5052, 6061 and 8011) with a 2-mm thickness were made thinner by cold rolling, obtaining three different thicknesses of (0.8, 1.0 and 1.2) mm. Sheets were then joined using the cold-metal-transfer (CMT) welding process. The Taguchi design of experiment (DOE) was carried out for the L_{27} orthogonal array with nine variables at three levels. Due to this optimization process, the welding decreased the formability of TWBs compared with the parent material and this was reflected in the forming behavior, represented by the strain-distribution profiles.

Keywords: tailor-welded blanks, aluminum alloy, incremental forming, cold metal transfer

Dandanes se zaradi ekonomičnosti, vladnih regulativ, dizajna vozil z zmanjšanjo težo in zaradi zmanjševanja stroškov v avtomobilski industriji uporabljajo prilagojeni varjeni surovci (angl. TWBs). Ta tehnika se uporablja tudi zaradi izboljšanja strukturne celovitosti in obnašanja pri nesrečah. Zaradi povečanja okoljskih vprašanj glede emisij izpušnih plinov in pomanjkanja naravnih virov, je treba zmanjšati težo vozila in izboljšati ekonomičnost porabe goriva. Posledično avtomobilska industrija uporablja prilagojene varjene surovce (TWB). V prispevku so bili trije sloji pločevine aluminija (5052, 6061 in 8011), z debelino 2 mm, stanjšani s postopkom hladnega valjanja na tri različne debeline (0,8, 1,0 in 1,2) mm. Plasti aluminija so bile nato združene s postopkom varjenja s kovinskim prenosom (angl. CMT). Taguchijeva metoda načrtovanja eksperimentiranja (angl. DOE) je bila opravljena za L_{27} ortogonalno polje z devetimi spremenljivkami na treh ravneh. Iz tega optimizacijskega procesa varjenje zmanjša sposobnost TWB v primerjavi z originalnim materialom, kar se odraža v obnašanju formiranj, ki ga predstavljajo profili razdeljevanja sevov.

Ključne besede: prilagojeni varjeni surovci, aluminijeva zlitina, postopno oblikovanje, hladen transfer kovine

1 INTRODUCTION

Aluminum and its alloys exhibit many attractive characteristics including light weight, high specific strength, high thermal and electrical conductivity. Aluminum also exhibits poor weldability due to its high reflectivity, low molten viscosity and the existence of oxide layers. Therefore, much research work on aluminum tailor-welded blanks with different thicknesses and various alloy combinations is in progress. Tailored blanks are the collective for semi-finished sheet products, characterized by the local sheet thickness, sheet material, coating or material properties. TWBs ensure that the components are light, stronger and provide the required functionality at a low cost. Incremental sheet-metal forming (ISMF) is a process, in which a sheet is formed incrementally through a progression of localized deformation. For small, batch-size products, there is no need for specialized dies in ISMF. Cold metal transfer (CMT) is an automated dip-transfer welding, characterized by controlled material deposition to the workpiece during the short circuit of the wire electrode.

Single-point incremental forming (SPIF) is a flexible sheet-metal-forming method adapted to form various complex shapes using a CNC milling machine, a multi-axis robot or a dedicated machine without the use of specific and costly tools, such as a punch and die.[1] SPIF can be used to form small or large pieces, based upon the machine size for the various components. Furthermore, the SPIF process, which is based on the forming limit diagram (FLD) used to achieve a higher formability compared to the conventional forming process, can be adapted to the materials such as the Al-Mg-Si alloy.[2] SPIF is used to form TWBs and also to improve the forming limit. However, the shape inaccuracy, which is usually an important limiting factor for SPIF applications is to be solved. Several mechanisms used for the enhanced formability of the SPIF process were already presented.[3] A further elaborate study on the incremental sheet forming regarding individual sheet quality is required. The mechanical properties of friction-stir-welded dissimilar aluminum alloys AA5052 and AA6061 using a cylindrical-pin tool are analyzed.[4] The cold metal transfer (CMT) is an innovative process based on short-circuiting metal transfer, introducing a relatively low heat into the weld seam and this reduces the formation of intermetallics and thermal distortion.[5] The welding of such hybrid joints is a big challenge due to large differences in the melting point and thermal expansion of aluminum alloys. The formation of excessive intermetallic compounds (IMCs) at elevated temperatures also reduces the joint strength.[6]

Cold metal transfer requires no spatter welding; it uses a low heat input during the welding and provides for a good performance of joining dissimilar metals, like aluminum and zinc-coated steel.[7] When joining three types of aluminum alloy with mild steel, design of experiments technique (DOE) is used to optimize the welding parameters. The effect of the intermetallic-layer thickness was also analyzed.[8] An advanced CMT method and optimized welding parameters were used to join dissimilar metals. The effect of the filler material on the wettability of the base material was also studied.[9] In this work, the single-point incremental forming of TWBs consisting of aluminum-alloy sheets made with cold-metal-transfer welding was studied and optimization of the process parameters was carried out using the Taguchi method.

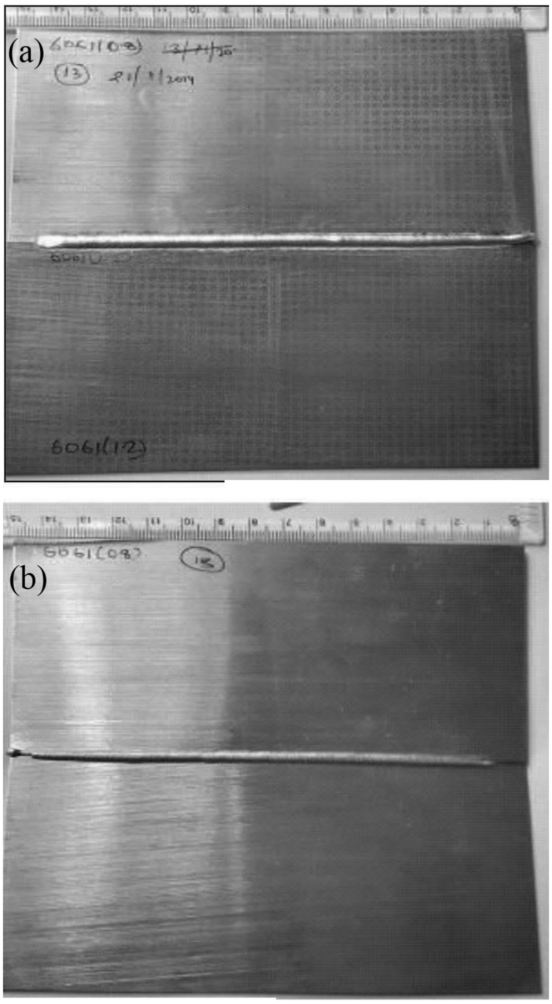

Figure 1: Specimens of TWBs: a) top surface, b) bottom surface

Table 1: Variables and levels of L_{27} DOE

No.	Variable	Level 1	Level 2	Level 3
1	1st material	5052	6061	8011
2	Thickness of 1st material	0.8 mm	1.0 mm	1.2 mm
3	2nd material	5052	6061	8011
4	Thickness of 2nd material	0.8 mm	1.0 mm	1.2 mm
5	Spindle speed	300 min^{-1}	450 min^{-1}	600 min^{-1}
6	Feed	300 mm/min	600 mm/min	900 mm/min
7	VSD	0.2 mm	0.4 mm	0.6 mm
8	Weld speed	400 mm/min	500 mm/min	600 mm/min
9	Lubricant	dry	coconut oil	grease

Table 2: L_{27} DOE (design of experiment) table using Taguchi method

No.	1st material		2nd material		Spindle speed (min^{-1})	Feed (mm/min)	VSD mm	Weld speed (mm/min)	Lubricant
	Series	Thickness (mm)	Series	Thickness (mm)					
1	5052	0.8	5052	0.8	300	300	0.2	400	dry
2	5052	0.8	5052	0.8	450	600	0.4	500	coconut
3	5052	0.8	5052	0.8	600	900	0.6	600	grease
4	5052	1.0	6061	1.0	300	300	0.2	500	coconut
5	5052	1.0	6061	1.0	450	600	0.4	600	grease
6	5052	1.0	6061	1.0	600	900	0.6	400	dry
7	5052	1.2	8011	1.2	300	300	0.2	600	grease
8	5052	1.2	8011	1.2	450	600	0.4	400	dry
9	5052	1.2	8011	1.2	600	900	0.6	500	coconut
10	6061	0.8	6061	1.2	300	600	0.6	400	coconut
11	6061	0.8	6061	1.2	450	900	0.2	500	grease
12	6061	0.8	6061	1.2	600	300	0.4	600	dry
13	6061	1.0	8011	0.8	300	600	0.6	500	grease
14	6061	1.0	8011	0.8	450	900	0.2	600	dry
15	6061	1.0	8011	0.8	600	300	0.4	400	coconut
16	6061	1.2	5052	1.0	300	600	0.6	600	dry
17	6061	1.2	5052	1.0	450	900	0.2	400	coconut
18	6061	1.2	5052	1.0	600	300	0.4	500	grease
19	8011	0.8	8011	1.0	300	900	0.4	400	grease
20	8011	0.8	8011	1.0	450	300	0.6	500	dry
21	8011	0.8	8011	1.0	600	600	0.2	600	coconut
22	8011	1.0	5052	1.2	300	900	0.4	500	dry
23	8011	1.0	5052	1.2	450	300	0.6	600	coconut
24	8011	1.0	5052	1.2	600	600	0.2	400	grease
25	8011	1.2	6061	0.8	300	900	0.4	600	coconut
26	8011	1.2	6061	0.8	450	300	0.6	400	grease
27	8011	1.2	6061	0.8	600	600	0.2	500	dry

2 EXPERIMENTAL PART

Three grades of aluminum (5052, 6061 and 8011) with a 2-mm thickness were made into sheets with three different thicknesses of (0.8, 1.0 and 1.2) mm, using

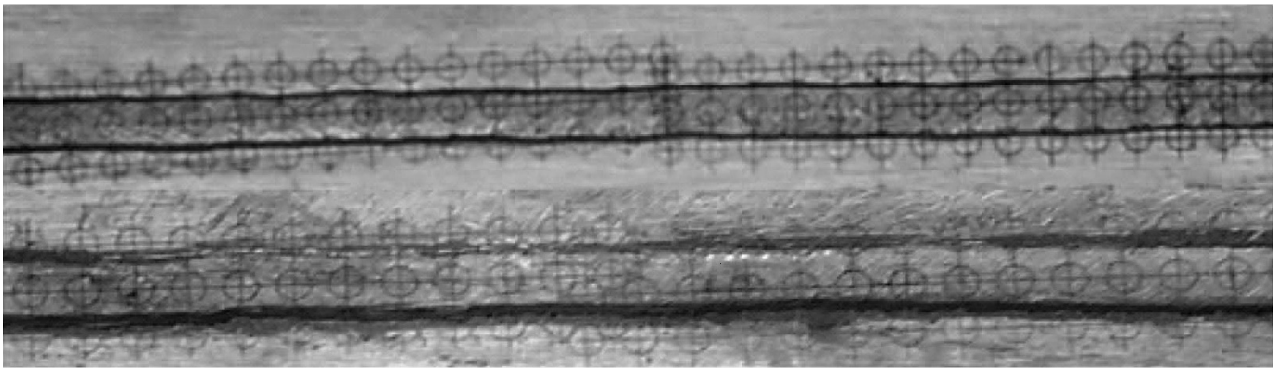

Figure 2: Grid marking on welds: TWB No. 1 (AA6061 (1.2 mm) + AA5052 (1.2 mm))

cold-rolling processes. The sheets were welded using cold-metal-transfer welding. Using the Taguchi method, the L_{27} orthogonal array with 9 variables in 3 levels were used for the design of experiments as shown in **Table 1**. The data regarding the L_{27} design of experiments are shown in **Table 2**. TWB specimens are shown in **Figure 1**. In this work, a 200W Nd-YAG laser is used for grid marking. The diameters of grid circles are 2 mm, the width of grid lines are 1 μm and the grid marking is shown in **Figure 2**.

2.1 Selection of the incremental-forming tool

A hemispherical-end tool with a 10-mm diameter and 100-mm length was used for incremental sheet-metal forming. With this tool, we can form the sheet metal, which is rigidly fixed onto a blank holder. The sheet forming is carried out by passing the feed incrementally to the tool.

2.2 Incremental sheet metal and straight groove

Single-point-incremental-forming tests were carried out using a 3-axis CNC machine as shown in **Figure 3**. In all the tests, a punch with a hemispherical head was used and grease/coconut oil was applied as the lubricant to reduce friction. An experimental blank of 150 mm × 150 mm was clamped to a properly designed framework. Circular grids of a 2-mm diameter were marked on the surfaces of aluminum sheets using a laser beam of 200 W, while the width of a grid line was 1 μm. The punch movement was determined with pure-stretching-deformation mechanics. Throughout the process, the punch head had a 10-mm diameter, and it determined the expansion of the blank, which underwent plastic deformation due to the punch movement, while its tool path was controlled using the part program. For each test, the tool trajectory depended on the testing conditions. Such trajectories included both the horizontal and vertical movements of the tool. The present work was focused on investigating the material formability. The test continuously varied with the wall angle and the wall angle of breakage depended upon the material, the thickness of the sheet and the grain orientation. Due to the localized action of the small hemispherical punch, the blank underwent a local thinning. Then the closest zone of the blank was deformed without a significant effect on the already deformed one. Therefore, forming limits must be identified, for any material, in terms of the critical threshold of the allowable local thinning. According to the above considerations, the strain path in incremental forming is typically very close to the major axis in the diagram and fracture strains are remarkably larger than the conventional stamping. Much higher strains can be achieved with incremental forming than with the traditional processes. During the straight-groove test, grooves were made in the direction of rolling. The size of grids is measured using a digital USB microscope.

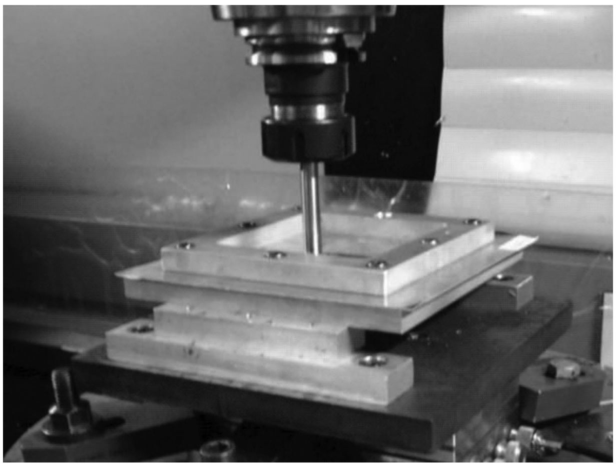

Figure 3: Experimental set-up

3 RESULTS AND DISCUSSIONS

The experiments from 1 to 27 were carried out as per the DOE table, as shown in **Table 2**. The welding image of the first experiment condition is shown in **Figure 4**. The formability achieved along the transverse of the weld was 0.955. A failure occurred on the weld because it exceeded the forming limit. The formability achieved along the weld was 0.32 and a failure occurred due to a

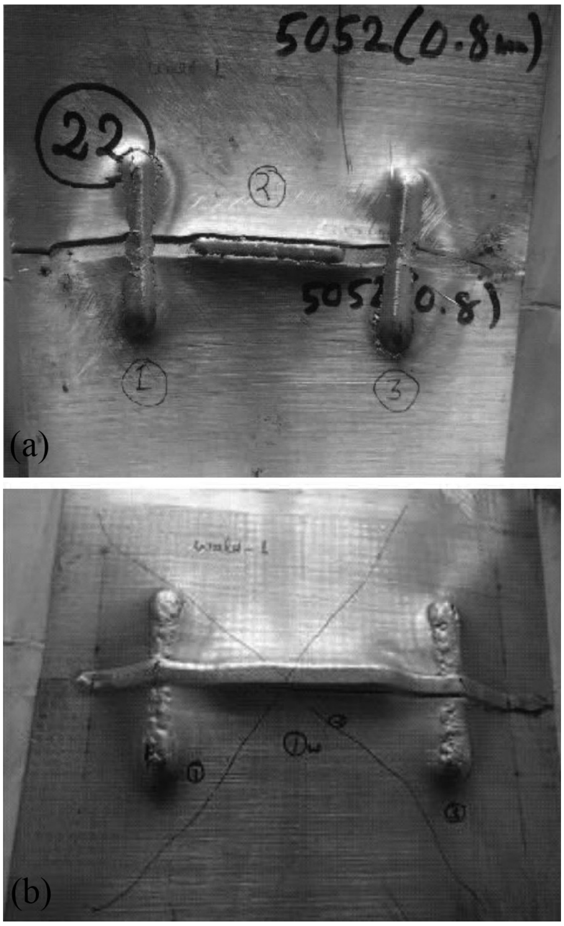

Figure 4: Images of formed TWB No. 1: a) top surface, b) bottom surface

poor weld quality. A tearing failure occurred along the weld direction. In the conventional forming, the *'n'* value for AA5052 (0.8 mm) is 0.1354, which is lower than the achieved formability for TWB No. 1. Similarly, the same process was repeated for all the conditions listed in **Table 2** and from the forming limit diagram, the formability values achieved along 'the transverse of the weld direction' and 'along the weld direction' are shown in **Table 3**.

Table 3: Formability achieved during forming

Ex. No.	Trans-verse of the weld	Along the weld	Ex. No.	Trans-verse of the weld	Along the weld
1	0.995	0.32	15	0.768	0.253
2	0.522	0.395	16	0.6	0.232
3	0.59	0.215	17	0.432	0.329
4	0.477	0.176	18	0.573	0.307
5	0.511	0.322	19	0.651	0.194
6	0.381	0.239	20	0.698	0.44
7	0.763	0.214	21	0.918	0.602
8	0.524	0.348	22	0.658	0.214
9	0.373	0.141	23	0.793	0.376
10	0.311	0.076	24	0.599	0.294
11	0.806	0.343	25	0.675	0.138
12	0.693	0.18	26	1.2	0.963
13	0.736	0.273	27	0.52	0.343
14	0.668	0.321			

3.1 Taguchi analysis: forming along the transverse of the weld direction versus variables

A response table for signal-to-noise ratios for the largest is better is shown in **Table 4**. The formability along the weldment and perpendicular to the weldment should be maximum until a rupture takes place. Hence, the larger the better condition is used. The formability parameters – 1st material thickness of 1.2 mm, 2nd material thickness of 0.8 mm, the spindle speed of 450 min^{-1}, the feed of 300 mm/min, VSD of 0.6 mm, the weld speed of 400 mm/min – are represented in the output graph based on the Taguchi analysis, which is same as that of the experiment.

4 CONCLUSIONS

Based on the results and discussion, the following conclusions are drawn:

- The *S/N* ratio for both directions is maximum for experiment No. 26.
- This indicates that the incremental-forming behavior during experiment No. 26 in optimum and its para-

Table 4: *S/N* ratio: largest is better

1st spindle			2nd spindle				
Level	1st series	thickness	2nd series	thickness	speed	feed	VSD
1	-5.272	-3.675	-4.104	-2.916	-4.094	-2.521	-3.596
2	-4.470	-4.356	-4.817	-4.978	-3.701	-5.023	-4.243
3	-2.801	-4.511	-3.620	-4.648	-4.747	-4.997	-4.703
Delta	2.471	0.837	1.197	2.062	1.045	2.502	1.107
Rank	2	9	6	3	8	1	7
Level	weld speed	lubricant					
1	-4.485	-4.178					
2	-4.717	-5.171					
3	-3.340	-3.193					
Delta	1.377	1.979					
Rank	5	4					

meters are optimum for the formation of tailor-welded blanks.

- During the groove formation in the transverse direction, a failure occurs on the weld because it exceeds the forming limit and tearing occurs along the weld.
- Welding decreases the formability of the TWBs compared with the parent material, which is reflected in the forming behavior, represented by strain-distribution profiles. This is due to the non-uniform strain distributions.
- The *S/N* ratios for the largest is better are proved by the statistics and the Taguchi analysis, which is same as that of the experiment.

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