SPRINGBACK OF FRICTION STIR WELDED SHEETS: EXPERIMENTAL AND PREDICTION

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Abstract

The objectives of the present work are, (i) to investigate the influence of tool rotational speed and welding speed on the springback of Friction Stir Welded (FSW) sheets, and (ii) to predict the same at different welding conditions using finite element simulations. The base sheets used are Al5052H32 and Al6061T6of 2.1 mm thickness. FSW sheets are fabricated at different tool rotational and translational (welding) speed. Springback has been evaluated during V-bending and compared for analyses. Hill's 1990 yield criterion is used in the finite element model for springback prediction. The springback of FSW sheets lie in between that of Al6061T6 and Al5052H32 base sheets. Reduction in springbackof FSW sheets is observed at higher rotational speed and welding speed, which correlates with the changes in σ_y/E ratio and n value of weld zone. There exists a close agreement between experimental and predicted springback values.

Keywords:Springback, FrictionStir Welding, Prediction, Weld zone

1 Introduction

Friction-stir welding (FSW) is a solid-state joining process. It involves joining of metals without filler materials. A constantly rotating cylindrical-shouldered tool with a profiled nib is transversely fed at a constant rate into a butt joint between twoclamped sheets. Frictional heat is generated between the wear-resistant welding components and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting. The resultant plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged together by the intimate contact of the tool shoulder and the pin profile (Mishra and Ma, 2005).

During sheet bending, while one side of the sheet metal is subjected to compressive stress, the other surface is subjected to tensile stress. An elastic recovery occurs because of the release of the elastic stresses in the bending process, after release of the load by withdrawal of the punch. This elastic recovery is called Springback. It is still a practical problem to predict the final geometry of the part accurately, after springback and to design appropriate tooling in order to compensate for springback. The trial and error, empirical methods, and advanced computational methods including finite element analyses are some of the effective means of predicting sheet springback.

Chang*et al.*(2002) investigated the springback characteristics of tailor-welded strips in U-bending processing. The tailor-welded strips were joined by the laser welding process and consisted of two types of thickness combinations of the SCP1 sheet and two weld orientations. The springback encountered by longitudinally welded strip was same as that of un-welded base sheets. In the case of the transverse welded strips, a significant reduction of the springback was observed in the thinner side compared with the same thickness of un-welded strip.

Tekaslan*et al.*(2008) concluded that the time to hold the punch on the sheets affects the springback. The punch must be kept for a definite period of time on the sheets to dispose the elasticity of sheet metal. Increasing the holding time, increases the spring-back. It is observed from Rao and Narayanan (2014)work that, with increase in shoulder diameter, rotational speed, and welding speed, the springback of friction stir welded sheets has reduced. FSW sheet springback is in between that of 6061 and 5052 base materials.

Ramulu*et al.*(2013) analyzed the effect of welding speed, rotation speed, plunge depth, and shoulder diameter on the formation of internal defects, axial force and torque during FSW of 6061T6 sheets. At higher welding speed, higher rotation speed, and higher plunge depth, internal defect free weld joints are produced. The axial force and torque were not constant and a large variation was seen with respect to FSW parameters that produced defective welds. In the case of defect-free welds, the axial force and torque were relatively constant. An extension of the work on forming limit indicates that with increase in the tool rotation speed, for a constant feed rate, the forming limit of friction stir welded blank has improved and with increase in feed rate, for a constant tool rotation speed, it has decreased. The strain hardening exponent of weld (n) increases with increase in tool rotation speed and it decreases with increase in feed rate(Ramulu*et al*., 2013).

The main objective of the present work is to study the effect of welding speed and rotational speed on the springback of FSW sheets, and predict the same using finite element simulations. For this, Al5052H32 and Al6061T6 are friction stir welded. The springback of welded and un-welded sheets are evaluated after V-bending. The same has been predicted and validated.

2 Methodology

The first step was to produce samples of friction stir welded sheets made of Al6061T6 and Al5052H32 by varying the tool rotational and translational (welding) speed. The tool rotational speed was varied from 600 RPM to 800 RPM, in 3 steps, and the tool translational speed was varied from 80 mm/min to 120 mm/min in 3 steps. The material properties and Lankford coefficients (*r*) of the base materials (Table 1, 2) and weld regions(Table 3) were determined by tensile tests by using ASTM standard sub-size 1 specimen dimensions (Abdullah *et al.*, 2001).Three trials were conducted to evaluate the tensile properties. Then 'V' bending tests were performed on all the welded blanks and base materials of dimensions 160mm×50mm. The weld was oriented longitudinally during bending experiments. The springback of these sheets (included angle) were measured within an hour, after V-bending was completed.Two trials were conducted to evaluate the springback in each case. A V-bending setup (Fig. 1) was fabricated to conduct experiments.

In order to predict the springback, finite element simulations wereperformed for V-bending (using the dimensions of setup in Fig. 1) of friction stir welded sheets using a commercially available elasto-plastic finite element code. This code uses the Lagrangian and explicit time integration techniques. The adaptive meshing that automatically refines the mesh was used for finite element simulations. The meshing was done with quadrilateral shell elements of the Belytschko–Tsay formulation. The average mesh size of about 2 mm was used throughout the sheet specimen and tools. The tools were modelled as rigid bodies. The base materials properties and weld zone properties obtained from experiments were incorporated during FE simulations. Hollomon's strain hardening law was used to describe the stress-strain behaviour of base material and weld zone. Hill's 1990 yield criterion was used as the plasticity model. The '*m*' value used in the yield criterion was optimized to have less error with experimental values. The sheets were subjected to springback explicit analysis, after bending, and springback angle was evaluated.

3 Results and Discussion

The tensile behaviour of the weld zone for different rotational speeds, at a constant translational speed, and for different translational speeds, at a constant rotational speed is shown in Fig. 2 and Fig. 3 respectively.

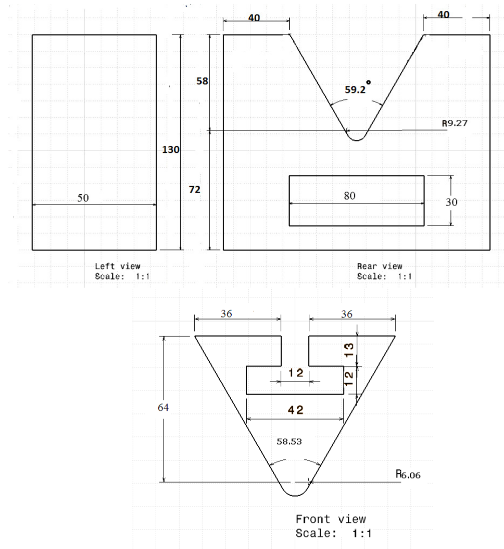

Figure 1 Schematic of die and punch in V-bending setup

Table 1 Tensile properties of Al6061T6 base sheet

Rolling direction (degrees)	E (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)	Uniform Elongation (%)	K (MPa)	n	r
0	23	206	282	0.096	397.6	0.141.	0.44
15	23	206	277	0.085	392.2	0.140	0.47
30	21	205	272	0.08	386.9	0.139	0.64
45	26	187	256	0.08	368.4	0.142	0.64
60	29	206	282	0.095	386.9	0.134	0.65
75	22	200	275	0.093	387.5	0.143	0.66
90	22	196	276	0.093	395.1	0.148	0.66

E – Elastic modulus, *K* – Strength coefficient, *n* – Strain hardening exponent, *r* – Plastic strain ratio

Table 2 Tensile properties of Al5052H32 base sheet

Rolling direction (degrees)	E (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)	Uniform Elongation (%)	K (MPa)	n	r
0	23	128	232	0.132	408.1	0.26	0.53
15	26	130	226	0.12	344.4	0.192	0.98
30	24	129	225	0.139	600.5	0.453	0.58
45	24	129	217	0.116	326.9	0.185	0.45
60	25	131	218	0.116	326.5	0.184	0.4
75	24	131	220	0.115	330.7	0.187	0.43
90	24	133	224	0.114	335.7	0.189	0.87

Table 3 Tensile properties of weld region

Rotational Speed (RPM)	Welding Speed (mm/min)	E (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)	Uniform Elongation (%)	K (MPa)	n	r
600	80	30	110	226	0.167	323.9	0.21	0.49
600	120	30	101	226	0.167	359.0	0.26	1.68
700	80	26	105	235	0.181	362.6	0.26	0.36
700	100	30	114	252	0.191	379.9	0.25	0.54
700	120	28	105	236	0.175	369.4	0.25	0.21
800	80	30	105	245	0.190	374.4	0.25	1.11
800	100	29	104	246	0.186	368.6	0.26	0.86
800	120	26	87	217	0.196	340.5	0.27	0.73

It is evident that the weld properties such as yield strength, UTS decreases with the increase in welding speed, at a constant rotational speed of 800 RPM. There is some improvement in the ductility of the weld zone with increase in welding speed and rotational speed (Fig. 2, Fig. 3). This improvement is due to the improvement in strain hardening exponent of weld zone (table 3).

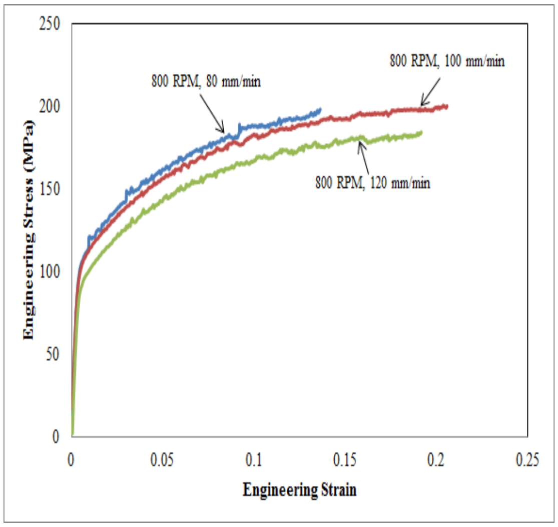

Figure 2Tensile behaviour of weld zone at different welding speeds

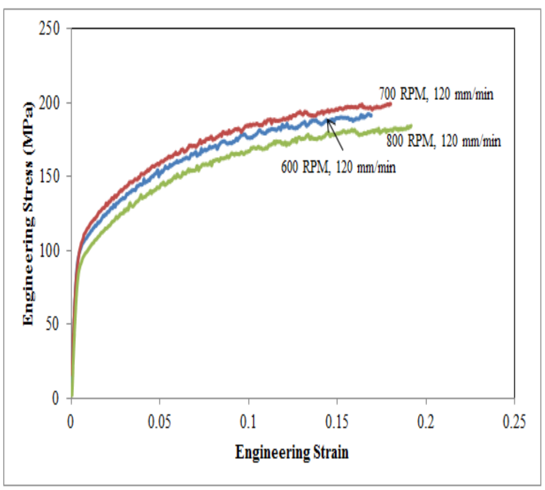

Figure 3Tensile behaviour of weld zone at different rotational speeds

The results obtained after performing V-bending on base material sheets and welded sheets are tabulated in Tables 4 and 5 respectively. It is evident that the springbackof Al5052 base material is less than that of all the welded sheets, which is lesser than the springbackof Al6061 base sheets. This is shown schematically in Figure 4.

Table 4 Springback of base materials

Springback angle	
Al6061T6	Al5052H32
64.77°	56.85°

Table 5 Springback of friction stir welded sheets

Rotational Speed (RPM)	Translational Speed (mm/min)	Springback angle (°)
600	80	62.86
700	80	58.97
800	80	60.46
600	100	63.10
700	100	62.32
800	100	61.05
600	120	61.52
700	120	60.64
800	120	59.95

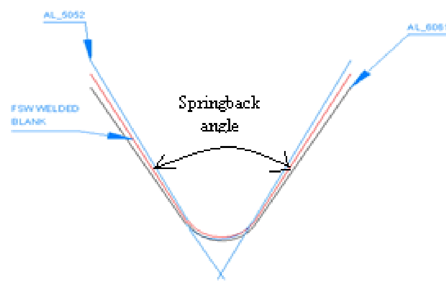

Figure 4 Representation of relative spring back of base materials and welded sheets

The influence of friction stir welding on the springback is due to the change in weld zone mechanical properties as compared to that of base materials. Two important mechanical properties, Yield strength to Young's modulus ratio and strain hardening exponent, of weld zone are evaluated for FSW conditions given in table 3. Because of the change in rotational speed and welding speed there is a significant change in Yield stress to Young's modulus ratio (σ_y/E) and Strain hardening exponent (n) of weld and this affects the springback of the welded sheets. Theoretically it is known that the springback increases with the increase of σ_y/E ratio and decrease of $n$value. The influence of rotational speed and welding speed on σ_y/Eratio, strain hardening exponent of weld zone and springback of welded sheets are shown in Fig. 5-7.

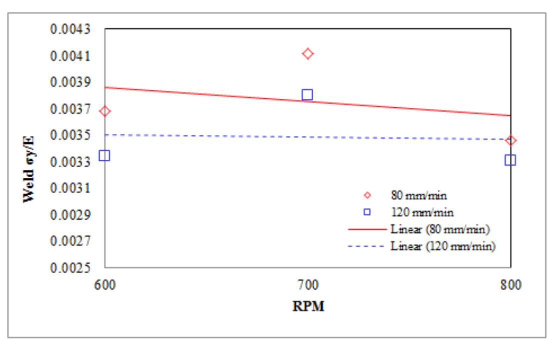

Figure 5Effect of rotational speed and welding speed on σ_y/E ratio of weld zone (Error in σ_y/E: 0.0001)

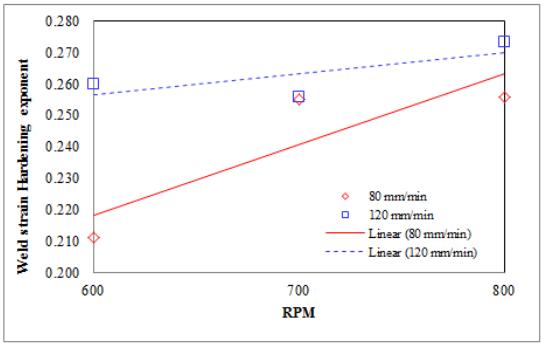

Figure 6Effect of rotational speed and welding speed on weld zone '*n*' value (Error in *n*: 0.002)

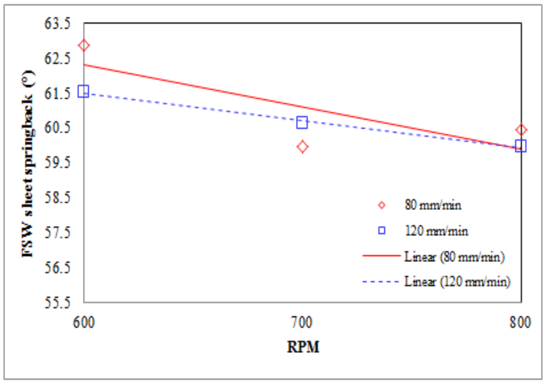

Figure 7 Effect of rotational speed and welding speed on springback of FSW sheets (Error in angle: 1.2°)

It is observed that springback decreases with increase in rotational speed and welding speed. With increase in rotational speed, σ_y/E ratio of weld zone decreases, and '*n*' value of weld zone increases, decreasing the springback. At the same time, for increasing welding speed from 80 mm/min to 120 mm/min, σ_y/E ratio of weld zone decreases, and '*n*' value of weld zone increases, decreasing the springback of FSW sheets.

As the materials used are Aluminium alloys, the yield criterion used is Hill's 90, and the Hills coefficient '*m*' is optimized such that for different *m* values between 1 and 3, the predicted and experimentally evaluated springback angles of base sheets and FSW sheets are compared (Table 6).

Table 6 Optimization of *m* value in Hill's 1990 yield criterion

m	Springback angle (°)	
	Al6061T6	Al5052H32
1.8	63.04	56.24
1.9	63.56	56.43
2	64.45	56.48
2.1	64.22	56.25
2.2	64.23	55.85
2.3	64.18	55.92

It is observed that the springbackvalues obtained at *m*=2 closely agree with the experimental springbackvalues of 64.77° and 56.85° for Al6061T6 and Al5052H32 base sheets respectively. Hence *m* = 2 was incorporated during FE simulations. The base sheets are considered as anisotropic material, and hence plastic strain ratios given in table 1 and 2 are utilized. The weld region is a mix of two Aluminium alloys, therefore simulations were performed twice, once by using the plastic strain ratios (*r*) obtained experimentally, indicating the weld zone to be anisotropic, and other by assuming that the weld region is isotropic, i.e., *r*=1. The values of springback found experimentally, and those predicted by simulations are shown in table 7. It is seen that the predicted value closely agree with experimental values for different FSW conditions. The error between the predictions and the experimental value is 2.33% and 2.26% in case isotropic and anisotropic weld zone assumptions respectively. Therefore the assumption of isotropic weld zone for springback predictions is acceptable, though anisotropic assumption will yield accurate results.

Table 7Comparison of experimental and predicted springback values

RPM	Welding Speed (mm/min)	Springback of FSW sheets (°)		
		From experiments	From Simulation (Isotropic weld)	From simulation (Anisotropic weld)
600	80	62.86	60.13	60.70
600	120	61.52	59.77	60.08
700	80	58.97	59.54	60.26
700	100	62.32	59.97	59.98
700	120	60.64	60.04	59.49
800	80	60.46	59.72	60.27
800	100	61.05	59.18	59.09
800	120	59.95	59.10	59.40

4 Conclusions

The following conclusions are drawn from the present analyses.
(i) The ductility of weld zone increases with increase in welding speed and rotational speed. This is due to the improvement of strain hardening exponent of weld zone at higher rotational speed and welding speed.
(ii) The springback of FSW sheets lie in between that of Al6061T6 and Al5052H32 base sheets.
(iii) Reduction in springbackof FSW sheets is observed at higher rotational speed and welding speed. Also the change in springback has got fair correlation with modifications in σ_y/E ratio and *n* value of weld zone.
(iv) A close agreement is obtained between experimental and predicted sprngback values at different FSW conditions. The usage of isotropic weld zone assumption is acceptable during springback prediction of FSW sheets, through anisotropic weld zone assumption yield slightly better results.

References

1. Mishra, R.S., and Ma, Z.Y. (2005), Friction stir welding and processing, Materials Science and Engineering R, Vol. 50, pp. 1–78
2. Chang, S.H., Shin, J.M., Heo, Y.M., Se, D.G. (2002), Springback characteristics of the tailor-welded strips in U-bending, Journal of Materials Processing Technology,Vol. 130–131, pp. 14–19.
3. Tekaslan, O., Gerger, N., Şeker, U. (2008),Determination of spring-back of stainless steel sheet metal in V bending dies, Materials and Design, Vol. 29, pp. 1043–1050.
4. DurgaRao, Ganesh Narayanan, R. (2014), Springback of Friction Stir Welded Sheets Made of Aluminium Grades during V-Bending: An Experimental Study, ISRN Mechanical Engineering, Volume 2014, Article ID 681910, http://dx.doi.org/ 10.1155/2014/681910.
5. Ramulu, P.J., Narayanan, R.G., Kailas, S.V., Reddy, J. (2013), Internal defect and process parameter analysis during friction stir welding of Al 6061 sheets, International Journal of Advanced Manufacturing Technology, Vol. 65,pp 1515-1528.
6. Ramulu, P.J., Kailas, S.V., Narayanan, R.G. (2013),Influence of tool rotation speed and feed rate on the forming limit of friction stir welded AA6061-T6 sheets, Proc. of IMechE, Part C: Journal of Mechanical Engineering Science, Vol. 227, pp. 520-541.
7. Abdullah, K., Wild, P.M., Jeswiet, J.J., Ghasempoor, A. (2001), Tensile testing for weld deformation properties in similar gage tailor welded blanks using the rule of mixtures, Journal of Materials Processing Technology, Vol. 112, pp. 91-97.

Acknowledgement

R. Ganesh Narayanan acknowledges DST, India and ARDB, India for sponsoring the projects. The present work is part of those projects.