Effects of process parameters on mechanical properties of friction stir welds using design of experiments

N Rajamanickam[a*] & V Balusamy[b]

[a]Department of Mechanical Engineering, [b]Department of Metallurgical Engineering,
PSG College of Technology, Coimbatore 641 004, India

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Friction stir welding is a relatively new joining process that is presently attracting considerable interest. This paper aims at establishing a relationship between welding parameters and mechanical properties in welding of 2014 type aluminum alloy using friction stir welding. A plan of experiment based on full factorial design has been performed. Samples have been prepared and welded by varying input parameters such as tool rotational speed and weld speed. The analysis of variance (ANOVA) is employed to investigate the effect of input parameters on mechanical properties of weld. A correlation is established between tool rotational speed, and weld speed with mechanical properties of weld by multiple linear regression. This study indicates that weld speed is the main input parameter that has the highest statistical influence on mechanical properties.

Keywords: Friction stir welding, Aluminum alloy 2014, Mechanical properties, Analysis of variance

The purpose is To establish the relationship between welding parameters and mechanical properties in the friction stir welding of aluminum alloy 2014, using design of experiments methodology.
Aluminum alloy 2014, valued for its high strength to weight ratio in aerospace applications, poses welding challenges due to its susceptibility to cracking during the welding process.

Experimental Setup

Table 1—Chemical composition of aluminum alloy 2014 [14]

Elements	Specification, (wt%)	Actual, (%)
Copper	3.9-5.0	4.59
Silicon	0.5-1.2	0.669
Magnesium	0.2-0.8	0.643
Iron	0.7 max	0.306
Zinc	0.25 max	0.132
Titanium	0.15 max	0.0071
Titanium + Zinc	0.2 max	—
Manganese	0.4-1.2	0.910
Chromium	0.1 max	0.014
Aluminum	Balance	92.72

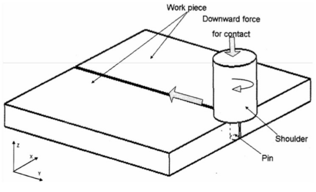

Fig. 1— Schematic diagram of friction stir welding

Table 3—Welding parameters used in the experimentation

Designation	Tool rotational speed (TRS), (rpm)	Weld speed (WS), (mm/min)
A1	600	8
A2	600	12
A3	600	20
B1	900	8
B2	900	12
B3	900	20
C1	1200	8
C2	1200	12
C3	1200	20

- Aluminum alloy 2014 selected for investigation due to difficulties in conventional fusion welding.
- Material used in the form of rolled plates, solution heat treated at 490-500°C and artificially aged at 180-200°C before welding.
- Test piece dimensions: 127 mm (length) × 60 mm (width) × 5.4 mm (height).
- Friction stir welding (FSW) conducted using Hartford vertical CNC machining center (model HV 35).
- Aluminum plates securely clamped on a flat fixture plate to prevent separation during welding.
- FSW tool description: 24 mm diameter shoulder, 6 mm diameter pin with 5 mm length and 1 mm left-hand screw pitch.
- Tool made of H-13 hot worked tool steel for wear resistance.
- Tool plunged into a 3 mm pilot hole in the workpiece, generating heat during traverse along the plate length.
- Welding performed with various tool rotational speeds and weld speeds using full factorial experimental design.
- Axial load of approximately 4000 N maintained on the FSW tool during welding, measured by a load cell.
- Visual and radiographic examination conducted on welded specimens to select defect-free samples.
- Standard test pieces prepared for tension and hardness tests by wirecut EDM process.
- Transverse tensile specimen dimensions per ASTM E8: 25.4 mm (length) × 6.3 mm (width).
- Total of nine experiments conducted, with two test specimens prepared and tested for each welded sample.

Effect on ultimate tensile Strength

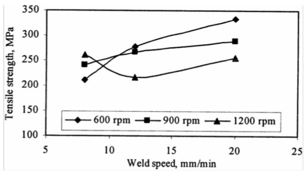

Fig. 2—Comparison of tensile strength

Role of Heat Input:

- the input welding parameters influence the heat generation and the flow of the plasticised material and eventually they affect the microstructure and the mechanical properties of the weld.
- Increase in weld speed within tested range correlates with higher ultimate tensile strength.
- **Impact of Tool Rotational Speed (TRS)**:
- Decreasing TRS parameter results in higher tensile strength.
- Reduction in TRS reduces heat input, leading to thinner thermomechanically affected zone (TMAZ) and heat affected zone (HAZ), consequently enhancing tensile properties.
- **Microstructure Influence:**
- Frictional heat leads to a softened region in the welded metal.
- Tensile properties influenced by welding defects and microstructure.
- **Defect-Free Welds and Fracture Locations**:
- Low welding speeds (8, 12 & 20 mm/min) resulted in defect-free friction stir welds.
- Fracture observed in TMAZ or HAZ on the advancing side of the joint.

Effect on elongation

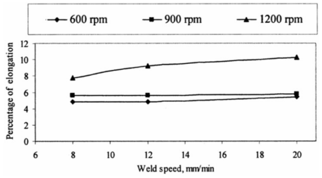

Fig. 3—Comparison of elongation

- **Elongation Variation:**
- Percentage of elongation along the transverse direction plotted against weld speed.
- **Influence of Heat Input:**
- Heat input strongly influences elongation properties.
- Plates welded with higher TRS and lower weld speed (high heat input) exhibit the highest elongation.
- **Impact of Tool Rotational Speed (TRS):**
- Increasing TRS leads to higher heat input and subsequently, increased elongation.
- **Experimental Observations:**
- Test plates welded with TRS of 1200 rpm and weld speed of 8 mm/min showed the highest elongation.
- Plates welded with TRS of 600 rpm and 20 mm/min yielded less elongation due to lower heat input.
- Higher heat input from increased TRS results in greater plastic deformation and elongation.

Effect on hardness

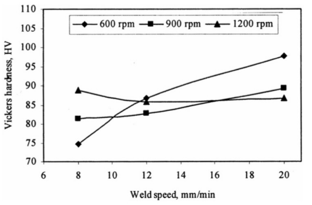

Fig. 4—Comparison of hardness

- **Hardness Measurement:**
- Vickers microhardness measurements conducted at the weld nugget zone using a Mitutoyo microhardness tester with a 100 g load.
- **Hardness Variation:**
- Variation of hardness (HV value) plotted against different TRS and weld speeds.
- **Impact of Heat Input:**
- Observations indicate a decrease in hardness with an increase in heat input.
- **Influence of Tool Rotational Speed (TRS) and Weld Speed:**
- TRS of 600 rpm at 8 mm/min weld shows lower hardness due to maximum heat input.
- Higher weld speed (e.g., 20 mm/min) results in higher hardness at the same TRS due to lower heat input.
- Higher heat input associated with lower weld speeds leads to lower hardness values.

Effect on microstructure

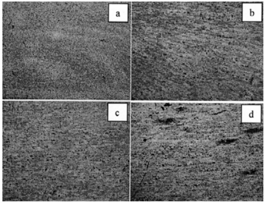

Fig. 6—Microstructures of (a) nugget zone, (b) TMAZ, (c) HAZ and (d) Parent metal (PM)

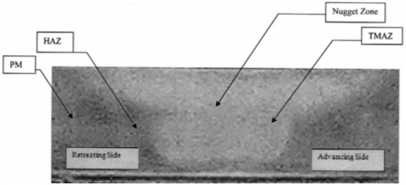

Fig. 5—Macrograph of the welded sample

- Cross-section of the FSW joint reveals distinct zones: weld nugget, TMAZ, and HAZ.
- **Weld Nugget:**
- Central region with fine grain size and onion ring structure.
- Fine grain size attributed to recrystallization process during welding.
- **TMAZ (Thermo-Mechanically Affected Zone) and HAZ (Heat-Affected Zone)**:
- TMAZ experiences deformation of grain structure without recrystallization.
- HAZ is affected by heat but not by deformation.

Conclusion from ANOVA analysis

Table 4—ANOVA for Tensile strength

Source of variance	Sum of squares (S)	Df(f)	Variance (S/f)	Variance ratio (Test F)	$F_{\alpha} = 5\%$	P
Weld speed (mm/min)	17157.69	2	8578.84	92.27	4.26	63.66
Tool rotational speed (rpm)	4789.3	2	2394.65	25.76	4.26	17.27
Interactions(I)	3876.66	4	969.16	10.42	3.63	13.15
Error	836.75	9	92.97	1.00	-	5.92
Total	26660.40	18	-	-	-	100.00

Df : Degree of freedom, P: Percentage of contribution

Table 5—ANOVA for elongation

Source of variance	Sum of squares(S)	Df(f)	Variance (S/f)	Variance ratio (Test F)	$F_{\alpha} = 5\%$	P
Weld speed (mm/min)	29.02	2	14.51	80.61	4.26	74.95
Tool rotational speed (rpm)	6.79	2	3.40	18.89	4.26	16.81
Interactions(I)	0.82	4	0.20	1.11	3.63	0.26
Error	1.62	9	0.18	1.00	—	7.98
Total	36.25	18	—	—	—	100.00

Df : Degree of freedom, P: Percentage of contribution

Table 6—ANOVA for hardness

Sourc of variance	Sum of squares (S)	Df(f)	Variance (S/f)	Variance ratio (Test F)	$F_{\alpha} = 5\%$	P
Weld speed (mm/min)	404.83	2	202.46	532.79	4.26	62.94
Tool rotational speed (rpm)	24.22	2	12.11	31.87	4.26	3.65
Interactions (I)	209.51	4	52.38	137.84	3.63	32.40
Error	3.42	9	0.38	1.00	—	1.01
Total	641.98	18	—	—	—	100.00

Df : Degree of freedom, P: Percentage of contribution

- ANOVA is a statistical method to analyze differences between group means.
- Weld speed emerges as the most influential parameter having highest percentage of contribution for tensile strength, elongation, and hardness of 63.66%, 74.95%, and 62.94% respectively.
- Higher weld speeds reduce heat input, minimizing the heat-affected zone (HAZ) and thermal distortion causing enhanced preservation of mechanical properties such as tensile strength, elongation, and hardness.
- Variations in weld speed exert the most pronounced effect on mechanical properties.