Process Parameter Optimization of Ultrasonic Assisted TIG Welding of Al 7075 and Al 6061Alloy Joints

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Abstract. The hot crack behavior (HCL) in the welding of Al 7075 alloy to Al 6061 alloy is examined by investigating the relationship between welding current and Ultrasonic Vibration Technique (UVT) input power. Through the utilization of Response Surface Methodology (RSM) and a Central Composite Design (CCD), the interactions between these parameters are explored. The significance of the developed model is demonstrated through ANOVA analysis, with UVT identified as the most influential parameter affecting the welding performance. By employing three-dimensional surface plots, an optimal parameter combination of 90 A welding current and 1.25 kW UVT input power was estimated, resulting in an anticipated HCL of -0.897 mm. Subsequent experimental validation under these conditions confirms the absence of cracks, thereby affirming the efficacy of the developed regression model and the successful application of RSM for optimizing process parameters.

Keywords: Tungsten Inert Gas Welding, Ultrasonic Vibration Technique, Response Surface Method, Hot Crack Length

1. Introduction

Al 7075 is a heat-treatable aluminum alloy with zinc as the primary alloying element while Al 6061 alloy is a medium to high strength heat-treatable alloy. These alloys exhibit higher strength to weight ratio, good ductility, and good corrosion resistance [1-2]. The dissimilar joining of these two materials leads to the combined properties of both materials, which makes this combination useful in military applications such as light combat aircraft (LCA), gun mount bases, pressure vessels, cargo tanks, submarine torpedo [3-5]. Aluminum materials can be generally welded using fusion welded process like tungsten inert gas welding (TIG) and metal inert gas (MIG) [6-7]. However, the joining of dissimilar aluminium 7075 and 6061 alloys retain a significant challenge for designers and technologists [8-9]. This challenge arises from issues such as hot cracking and porosity, which stem from differences in solidification characteristics of the alloys. These differences are caused by variations in chemical composition, melting point, coefficient of thermal expansion, and mechanical properties [10].

TIG welding, or GTAW, utilizes a non-consumable tungsten electrode and inert gas to achieve high-quality welds, offering faster speeds, reduced distortion, precision, and control, making it suitable for welding of aluminium alloys [11-13]. However, Precise welding requires managing welding speed, current, voltage, electrode diameter, gap, material, and shielding gas, tailored to machine specs, to minimize defects. [14-15]. The welding current plays a crucial role in TIG welding of aluminum alloys, influencing the heat input and the depth of

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penetration, thus directly impacting the weld quality. Proper control and adjustment of the welding current are essential for achieving sound and high-quality welds in aluminum alloy TIG welding applications [16-17].

Researchers have been suggested that the improvement in weld quality may be accredited to refinement in fusion zone grain size and structure [18]. It has also been found that the controlled heat input decreases the distortion and warpage which helps in improvement of mechanical properties [19-20]. Ultrasonic vibration technique (UVT) is more beneficial due to its impact on weld microstructure and mechanical properties. It reduces residual stress, and distortion [21]. The ultrasonic vibration assisted welding process is a significant parameter in controlling weld bead characteristics by faster the cooling rate, smaller the grains formed thus resulting in maximum tensile properties [22].

To prevent defects in Al 7075 and Al 6061 alloy welding, optimization of parameters by ensuring proper preheating, controlling welding speed, employing favorable joint designs, selecting compatible filler materials like Al 5356, and maintaining shielding gas quality is essential [23]. Hot cracking, a common issue, can be mitigated by addressing factors such as controlled cooling rates, suitable joint configurations, and post-weld heat treatment, contributing to a more reliable and defect-free welding process [24-25]. Therefore, this study investigates the feasibility of welding dissimilar aluminium alloys using an ultrasonic vibration assisted TIG welding machine. The effect on hot cracking behavior is analyzed through optimizing the weld input parameters with the aim of minimizing the hot crack length.2. Experimental Procedure. In this study, dissimilar butt joints were prepared using the TIG welding (Rilon 315P AC/DC) process, both with and without the application of ultrasonic vibrations. The experimental setup is depicted in Fig.1. The chemical composition of the materials, detailed in Table 1, included Al 6061 and Al 7075 base plates, along with Al 5356 filler rod. The base plates were machined to the dimensions of 75 mm × 45 mm × 4 mm, and chamfered at 45° groove on the 75 mm edge for the ‘single V groove’ configuration weld joint. Al 5356 was chosen as the filler due to its resistance to cracking and its ability to match the mechanical properties of the base metals [26]. The Al5356 filler rod with a diameter of 3.15 mm was utilized for welding trials, and argon gas was employed for shielding during the welding process.

Fig1. Ultrasonic assisted TIG welding machine setup

To ensure proper alignment and gap maintenance, the specimens to be welded were properly clamped on a fixture. Ultrasonic vibrations were generated using a magneto restrictive transducer equipped with an SS304 horn (Reltec, Russia) and transferred to the weld zone with the help of a specially designed fixture. The details of the fixture design have been adapted from literature and are discussed elsewhere [27]. Ultrasonic vibrations with a frequency of 20 kHz and an input power varying from a range of 1.25 kW to 1.75 kW were applied during the welding process.

Table1. Chemical composition (wt%) of base metal and filler metal.

Mat Name	Cu	Fe	Mg	Mn	Si	Zn	Al
Al 6061	0.30	0.6	0.9	0.05	0.7	0.20	Bal
Al 7075	1.5	0.3	2.5	0.04	0.08	5.6	Bal
Al 5356	0.05	0.35	4.75	0.16	0.10	0.06	Bal

Welding Current (WC) and application of UVT were the choosen process parameters and have significant effect on hot cracking behavior in Al alloys. Pilot experiments were conducted to identify the working range of WC and UT based on absence of cracking, porosity and lack of fusion.Using a Central Composite Design (CCD) matrix, a two-factor, two-level Response Surface Methodology (RSM) technique was used for the Design of Experiments (DOE). With an alpha value of 1, this matrix had four cube points, five centre points, and four-star points, representing an exact duplication of a two-factor factorial design. Thirteen sets of coded variables were also included. The middle-had gaps between the upper and lower boundaries that were evenly spaced, and the higher and lower ranges of each parameter were coded as +1 and -1, respectively. Trial experiments were conducted by varying welding current (70, 90, 110 A) and ultrasonic treatment (0, 1, 2) whereas 0 means without UT, 1 means low power, 2 means high power. Input parameters with their levels are given in Table 2.

Table 2. Level indication table

Input Parameter	Symbol	Level		
		-1	**0**	**+1**
Welding Current	WC	70	90	110
Ultrasonic Vibration	UVT	0	1	2

The statistical steps employed in Response Surface Methodology (RSM) include ANOVA, regression analysis, and response surface plots of the interaction effects of the parameters to determine the optimum parameter combination. ANOVA is utilized to calculate the interactive effects of the process parameters, while HCL is considered a response variable that is a function of the Welding current and UVT on time, as expressed in Equation 1 [30].

$$y = f(WC, UVT)\ . \qquad (1)$$

Where, y is the response factor.

$$Y = b_0 + n\sum_{i=1} b_i x_i \left(\sum_{i=0}^{n} b_i x_i\right)^2 + \sum_{i=1}^{n-1}\sum_{j=1}^{n} b_{ij} x_{ij} \ . \qquad (2)$$

- Y is the predicted or expected value of the dependent variable.
- x_i and x_j are the two distinct independent or predictor variables.
- b_0 is the value of Y when all of the independent variables (X_1 and X_2) are equal to zero.
- b_i=linear coefficients; b_{ii}= quadratic coefficients; and b_{ij}=interaction coefficients

The Central Composite Design (CCD) was used to explore various combinations of process parameters and their impact on the Hot Crack Length. A second-order polynomial regression equation was fitted to the experimental results, and the ANOVA results indicated the model's significance. The coded factors in Equation 2 can be used to predict the response for different factor levels, with high and low levels coded as +1 and -1, respectively.

The significance of the regression coefficient was measured by p-value, if p-value is less than 0.05 the regression coefficient is significant otherwise insignificant [28]. The response of the process parameter was used to develop a mathematical model shown in Equation 3.

$$HCL=235.5 - 4.40*WC-52.4*UVT+0.02283*WC^2+ 12.41*UVT^2+0.163WC*UVT. \qquad (3)$$

Table 3. ANOVA table for Hot Crack analysis

Source	DF	Adj SS	Adj MS	F - Value	P- Value	Remarks
Model	5	2122.64	424.527	15.02	0.001	Significant
Linear	2	1034.57	517.286	18.30	0.002	
WC	1	42.29	42.294	1.50	0.261	
UVT	1	992.28	992.278	35.11	0.001	
Square	2	1045.42	522.712	18.49	0.002	
WC*WC	1	230.27	230.267	8.15	0.025	
UVT*UVT	1	425.07	425.072	15.04	0.006	
2-Way Interaction	1	42.64	42.641	1.51	0.259	
WC*UVT	1	42.64	42.641	1.51	0.259	
Error	7	197.84	28.263			
Lack-of-Fit	3	196.09	65.363			
Pure Error	4	1.75	0.438			
Total	12	2320.48				

Model Summary		
Std.dev	**R-Sq**	**R-Sq (adj)**
5.31632	91.47%	85.38%

Table 4. Experimental Data vs Predicated Data

S. No	WC	UVT	Expt. Data	Pred. Data	Error
1	**70**	**0**	**44.60**	**39.367**	**5.233**
2	90	0	14.28	24.423	-10.143
3	90	1	0.00	-0.897	0.897
4	90	1	0.00	-0.897	0.897
5	**110**	**2**	**6.39**	**8.443**	**-2.053**
6	70	2	6.63	7.027	-0.397
7	70	1	5.06	10.787	-5.727
8	90	2	0.00	-1.397	1.397
9	90	1	1.48	-0.897	2.377
10	110	0	31.30	27.743	3.557
11	**90**	**1**	**0.00**	**-0.897**	**0.897**
12	90	1	0.00	-0.897	0.897
13	110	1	2.67	5.683	-3.013

The experiment utilized a Central Composite Design (CCD) to vary input parameters, and the results were fitted to a polynomial equation through regression analysis as shown in Equation 2[29].

The fractures in the welded specimens were detected through the liquid penetrant test (LPT).After applying penetrant and developer to the welded specimens, the obtained pictures were exported to the Image-J programme so that the fracture length could be calculated. The Hot Crack Length (HCL) in joints resulting from various combinations of weld process parameters was calculated and presented in Table 4. Fig. 2 represents the specimens of extreme and optimum conditions of the input parameters indicating the presence of HCL.

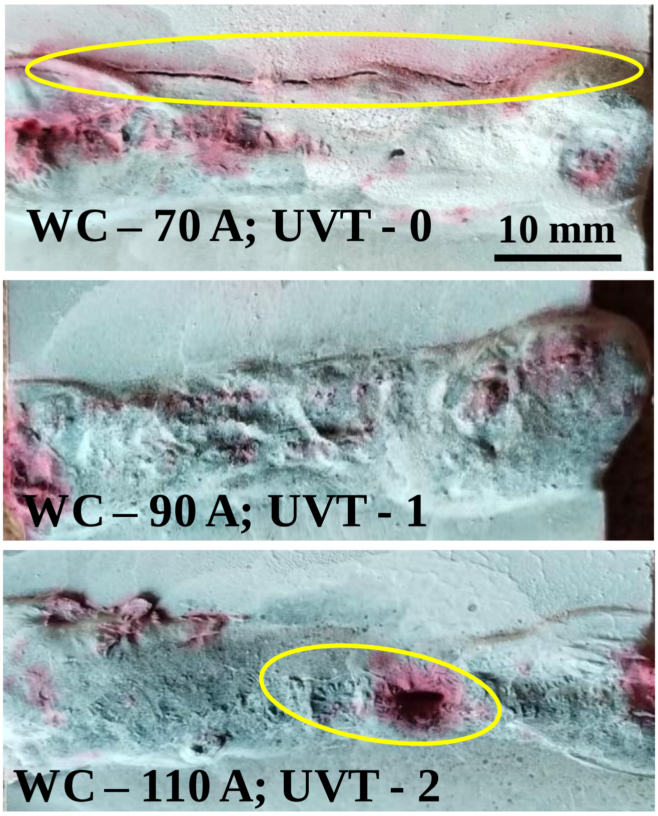

Fig2.TIG welded specimens at various input parameters

Upon analysis of the results, it is observed that the deviation is minimized when the parameters are set to a Welding Current of 70 A with no Ultrasonic Vibration Technique, and it peaks when the parameters are configured with a Welding Current of 110 A and a Ultrasonic Vibration Technique setting of 3. As a result, the optimal combination of process parameters is determined to be a Welding Current of 90 A coupled with a Ultrasonic Vibration Technique setting of 1.The optimal combination of process parameters is displayed in Table 5.

Table 5. Optimum Process Parameter Identified

S. No	Condition	Welding Current	Ultrasonic Vibration Technique	Remark
1	Low	70	0	Rejected
2	**Medium**	**90**	**1**	**Optimum**
3	High	110	2	Rejected

3.Result and Disscusion

3.1 Response Surface Analysis

The ANOVA result in Table 3 demonstrates the significance of the quadratic polynomial model in representing the relationship between Hot Crack Length and the model input parameter, with a p-value of 0.001. The coefficient of determination (R^2) value, compared to the adjusted R^2, is used to assess the adequacy of the developed model [30]. In this case, the high R^2 value of 0.9147 and adjusted R^2 value of 0.8538 indicate that the model accounts for 91.47% of the variation in the experimental data.

The strong relationship between input factors (welding current, filler wire type, and the application of UVT) and the response factor (Hot Crack Length) yielded an R-square value of 91.47%, which was is accepted based on ANOVA at a confidence level of 95%, further emphasizing the model's significance and adequacy. Moreover, the strong agreement between predicted and experimental values, along with data points closely aligning with the ideal fit line in Fig 3, strongly supports the model's adequacy and its ability to accurately estimate the response.

In statistical analysis, the ANOVA model relies on a 95% confidence level assumption for robustness. The R-squared value elucidates the variance explained by independent variables. Notably, the confidence level doesn't directly influence R-squared but serves as a metric for coefficient certainty and model fit. The reported results align with statistical norms at a 95% confidence level, affirming the model's goodness of fit.

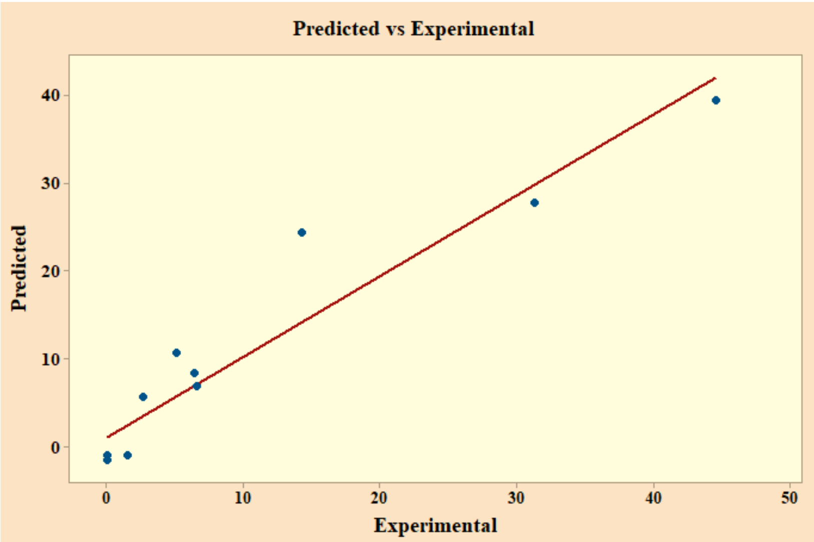

Fig 3. Predicted vs Experimental value of HCL

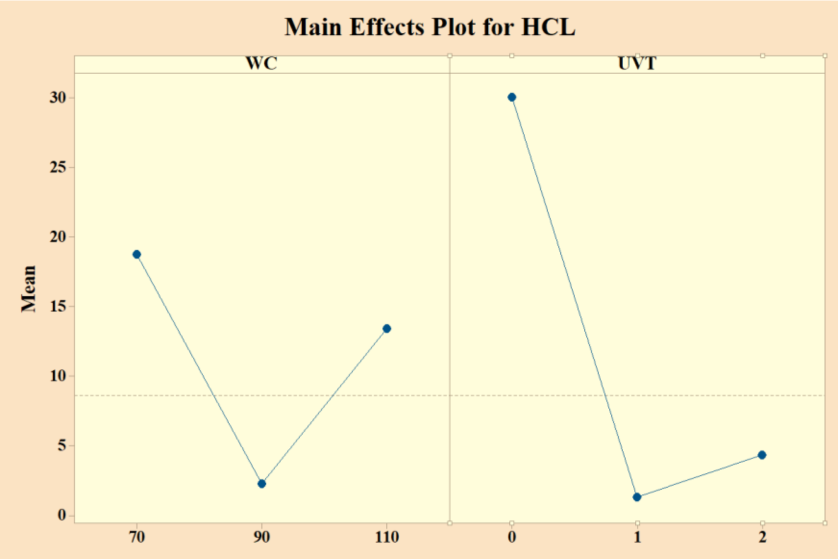

Fig 4. Interaction effect between process parameters and HCL

The main effects plot, illustrates the interaction effect between process parameters and their impact on Hot Crack Length (HCL), as depicted in Fig 4. The plot demonstrates the effect of current on HCL, showing that an increase in current leads to a corresponding increase in HCL, as evidenced in Fig 4. Additionally, the application of UVT alongside the welding current results in a decrease in HCL. This simultaneous decrease in HCL, as a result of the application of UVT with the welding current, is accurately represented in the plot.

The observation of minimized Hot Crack Length (HCL) at a welding current of 90A and in the presence of low power UVT highlights the optimum combination of input parameters in reducing HCL. This observation is clearly supported by the findings depicted in Fig 4, emphasizing the substantial impact of UVT application on the reduction of HCL

As seen in Fig. 5, the 3D response surface plots were created using the established empirical connections to investigate the interaction effects of process factors on the HCL. The vertical axis in the surface plot, which essentially fills the graphical space, shows the response as a function of each pair of process parameters, whereas the horizontal axes indicate two continuous input parameters.
The highest hot cracking value was observed at a welding current of 70 A in the absence of UVT, as depicted in Fig 5. Conversely, the lowest hot cracking was observed at a welding current of 90 A and the application of UVT at an input power of approximately 1.25 kW, as illustrated in Fig 5.

UVT is the most significant process parameter that affects the HCL, as indicated by its highest F-value in ANOVA Table 4. To validate the predicted value, an experiment was performed under this optimum combination of input parameters. The experimental value obtained showed no cracks and very minimalistic cracks, which closely align with the predicted value. Therefore, the developed regression model is deemed to be satisfactory.

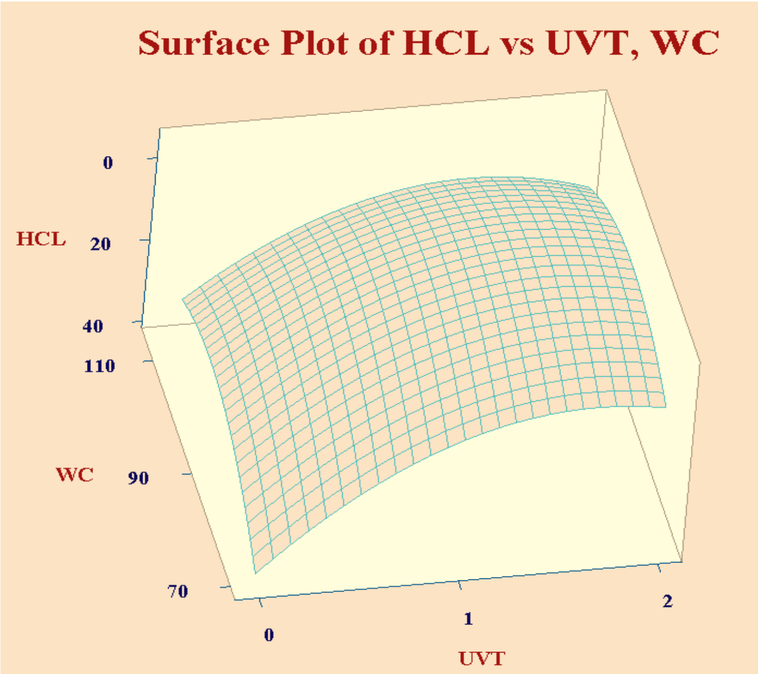

Fig 5. 3D surface plot of HCL vs UVT, WC

5. Conclusion

The parameters utilized in this study to determine the Hot Crack Length (HCL) and evaluate the desired combination of input parameters, namely welding current and UVT, under optimum conditions, comply with the standard. The results of the ANOVA test demonstrate the significance of the developed model. It is evident that UVT has the highest F-value, indicating its status as the most crucial process parameter affecting the performance characteristics.

In this study, the optimum combination of process parameters was determined to be a welding current of 90 A and UVT input power of 1.25 kW. The experimental observation of no cracks at this condition validates the developed regression mathematical model, thereby demonstrating the effective application of RSM with an appropriate Central Composite Design (CCD) for process parameter optimization.

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