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# Effect of process parameters on tensile strength of friction stir welding A356/C355 aluminium alloys joint †

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**Abstract**

In the present investigation, A356/C355 aluminium alloys are welded by friction stir welding by controlling various welding parameters. A356 and C355 aluminium alloys materials have a set of mechanical and physical properties that are ideally suited for application in aerospace and automobile industries and not widely used because of its poor weldebility. To overcome this barrier, weldebility analysis of A356 and C355 aluminium alloys with high speed steel (Wc-Co) tool has been investgated. An attempt has been made to investigate the influence of the rotational speed of the tools, the axial force and welding speed on tensile strength of A356/C355 aluminium alloys joint. The experiments were conducted on a milling machine. The main focus of investigation is to determine good tensile strength. Response surface methodology (box Behnken design) is chosen to design the optimum welding parameters leading to maximum tensile strength. The result shows that axial force increases, tensile strength decreases. Whereas tool rotational speed and welding speed increase, tensile strength increases. Optimum values of axial force (3 /KN), tool rotational speed (900 RPM) and welding speed (75 mm/min.) during welding of A356/C355 aluminium alloys joint to maximize the tensile strength (Predicted 223.2 MPa) have been find out.

*Keywords*: Friction stir welding; Milling machine; RSM; Tensile strength; HAZ; TMAZ

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## 1. Introduction

The Friction stir welding (FSW) technology is being targeted by modern aerospace industry for high performance structural applications. If compared to traditional welding techniques, FSW strongly reduces the presence of distortions and residual stresses. FSW technology requires a thorough understanding of the process and consequent mechanical properties of the welds in order to be used in the production of components for aerospace applications [1]. Based on friction heating at the facing surfaces of two sheets to be joined, in the FSW process a special tool with a properly designed rotating probe travels down the length of contacting metal plates, producing an highly plastically deformed zone through the associated stirring action. The localized thermomechanical affected zone is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with the tool. Some aluminium alloys can be resistance welded with an extensive surface preparation due to oxide formation. On the other hand, FSW can be used to join most Al alloys as the surface oxide is not a deterrent for the process and therefore no particular cleaning operation is needed prior to welding. In FSW the work piece does not reach the melting point and the mechanical properties of the welded zone (especially when attention is focused on heat-treatable light alloys) are much higher compared to those provided by traditional techniques [2]. FSW is considered to be the most significant development in metal joining in a decade and is a ‘‘green’’ technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease [3]. FSW joints usually consist of four different regions, they are: (a) unaffected base metal (b) heat affected zone (HAZ) (c) thermo-mechanically affected zone (TMAZ) and (d) friction stir processed (FSP) zone. The formation of above regions is affected by the material flow behaviour under the action of rotating non-consumable tool.

## 2. Selection of the marerial

### *2.1 Weld plates*

In this study, A356 and C355 aluminium alloys are selected.

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Table 1. Chemical composition of A356 alloy (wt %).

| Si | Fe | Cu | Mn | Mg | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|
| 6.5-7.5 | 0.2 | 0.2 | 0.1 | 0.25-0.45 | 0.1 | 0.1 | Balance |

Table 2. Chemical composition of C355alloy (wt %).

| Si | Fe | Cu | Mn | Mg | Ti | Oth | Al |
|---|---|---|---|---|---|---|---|
| 5.2 | 0.2 | 1.33 | 0.14 | 0.53 | 0.1 | 0.15 | Balance |

Table 3. Properties of tool material, High speed steel (Wc-Co).

| Properties | Unit | (WC-Co) tool material |
|---|---|---|
| Red hardness temp | $^{0}C$ | 900-1050 |
| Poisons ratio | - | 0.28 |
| Coefficient of thermal expansion / $10^{-6}$ $K^{-1}$ | $20^{0}C$ | 4.9-5.1 |
| Thermal conductivity | W/mK | 76-95 |
| Tensile strength, ultimate | Mpa | 1050 |

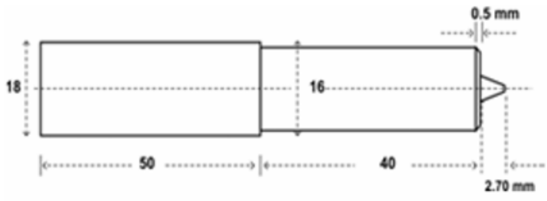


Fig. 1. Tool dimension.

Both have very good mechanical strength, ductility, hardness, fatigue strength, pressure tightness, fluidity, and machinability. But C355 have more tensile strength, hardness and toughness as compared to Alloy A356. The chemical composition of A356 and C355 are shown in Tables 1 and 2, respectively.

### *2.2 Tool material*

In the present study, a WC-Co hard alloy tool was used to friction stir weld. Tungsten carbide (WC) has been well known for its exceptional hardness and wear/erosion resistance. Matrices of ductile metals, such as cobalt, greatly improve its toughness so that brittle fracture can be avoided. Cemented tungsten carbides are commercially one of the oldest and most successful powder metallurgy products The toughness of WC is said to be excellent and the hardness is 1650 HV. The material is apparently also insensitive to sudden changes in temperature and load during welding trials [4]. The properties and tool dimension of WC-Co are shown in Table 3 and Fig. 1, respectively.

## 3. Experimental procedure

A milling machine was used for friction stir processing

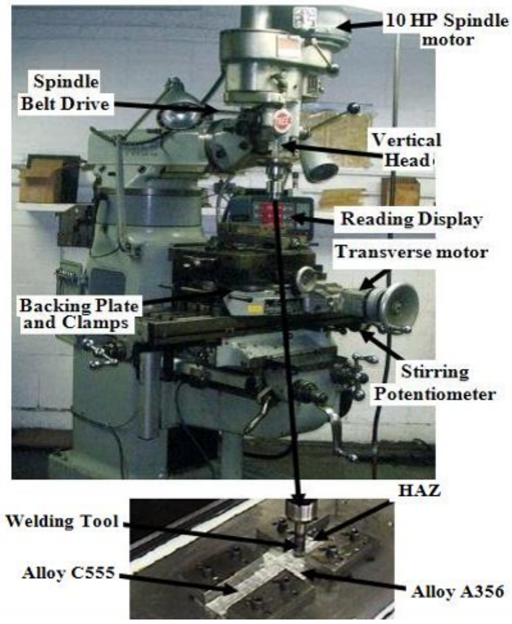


Fig. 2. Friction stir welding milling machine.

(FSW) of dissimilar aluminum alloys (C355 and A356). The machine was a maximum speed of 4500 rpm and 10-horse power. Tool tilt angle kept $1.5^{0}$. Double sided welding has been carried out for all 17 runs.

In this process, a WC-Co hard alloy tool is rotated into the joint line between two pieces of plate material (A356 and C355), which are butted together as shown in Fig. 2. The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. The length of the pin is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work piece surface. The pin is then moved against the work piece, or vice-versa. Frictional heat is generated between the wear resistant welding tool shoulder and pin, and the material of the work-pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point (hence cited a solid-state process). As the pin is moved in the direction of welding the leading face of the pin, assisted by a special pin profile, forces plasticized material to the back of the pin whilst applying a substantial forging force to consolidate the weld metal [5].

### *3.1 Selection of process parameters of friction stir welding and their levels*

There are various process parameters of FSW milling machine affecting the welding characteristics. On the basis of literature review and same pilot investigations, the following process parameters have been selected for study. Their ranges are given in Table 4.

Table 4. Process parameters with their ranges.

| S.No. | Input parameters | Range |
|---|---|---|
| 1 | Axial force (/KN) | 3 - 5 |
| 2 | Welding speed (mm/min) | 25- 75 |
| 3 | Tool rotational speed (RPM) | 800 - 900 |

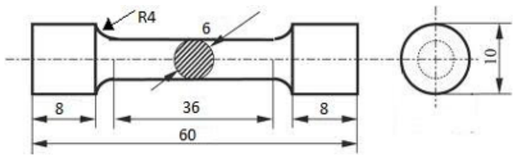


Fig. 3. Specification and dimension of tensile specimen.

Fig. 4. Tensile pieces of alloys (C355 + A356) after FSW.

## 4. Response surface methodology

The response surface methodology is used to design the experiment for the given problem and the problem formulated with the following steps. In this study, three parameters are used as levels that maximize the yield (y) of a process. The process yield is a function of the different constituents, say

$$y = f(x_1, x_2, x_3) + \epsilon \quad (1)$$

where Є represents the noise or error observed in the response y. if we denote the expected response (tensile strength) by $E(y) = f(x_1, x_2, x_3, x_4, x_5) = \eta$, then the response represented by

$$\eta = f(x_1, x_2, x_3) \quad (2)$$

is called a response [6].

Box-Behnken design is used to further study the quadratic effect of factors after identifying the significant factors using screening factorial experiments.

## 5. Planning of experiments

Welding of A356 and C355 alloys were carried out on FSW milling machine as per the plan of experiments tabulated in Table 5 and measured tensile strength are also given in Table 5.

Table 5. Design matrix and experimental results.

| Standard order | Axial force (/KN) | Welding speed (mm/min) | Rotational speed (RPM) | Tensile strength (MPa) |
|---|---|---|---|---|
| 1 | 5.00 | 50.00 | 800.00 | 130 |
| 2 | 4.00 | 25.00 | 900.00 | 210 |
| 3 | 4.00 | 75.00 | 800.00 | 150 |
| 4 | 4.00 | 25.00 | 800.00 | 120 |
| 5 | 4.00 | 75.00 | 900.00 | 340 |
| 6 | 4.00 | 50.00 | 850.00 | 220 |
| 7 | 5.00 | 25.00 | 850.00 | 170 |
| 8 | 4.00 | 50.00 | 850.00 | 215 |
| 9 | 4.00 | 50.00 | 850.00 | 229 |
| 10 | 3.00 | 25.00 | 850.00 | 270 |
| 11 | 3.00 | 75.00 | 850.00 | 340 |
| 12 | 5.00 | 50.00 | 900.00 | 230 |
| 13 | 5.00 | 75.00 | 850.00 | 280 |
| 14 | 3.00 | 50.00 | 800.00 | 200 |
| 15 | 4.00 | 50.00 | 850.00 | 227 |
| 16 | 4.00 | 50.00 | 850.00 | 225 |
| 17 | 3.00 | 50.00 | 900.00 | 340 |

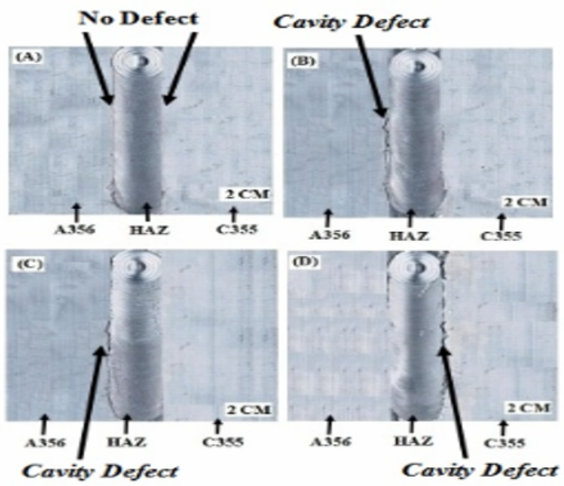


Fig. 5. Macroscopic appearances of A356 and C355 Al alloys joint.

## 6. Result and discussion

### *6.1 Macrostructures analysis*

During the friction stir welding of A356 and C355 aluminium alloys on milling machine, the tool shoulder is to supply a sufficient forge effect on the weld surface (surface of A356 and C355) to obtain a weld with good formation. To reduce the axial plunge force and the welding torque, only a sub-size concave shoulder is designed on the tool pin, which has no capability to prevent all plasticized materials from escaping from both sides of the tool during the FSW. When the plasticized materials are extruded out from both sides of the tool,

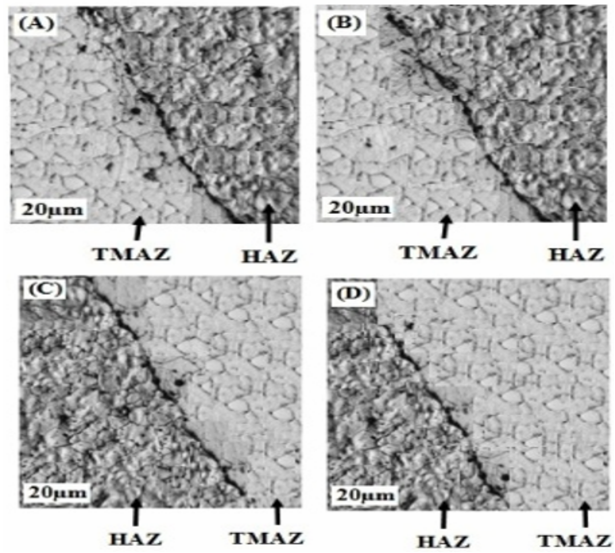


Fig. 6. Microstructure of A356 and C355 Al alloys joint.

serious flash defects appear on both sides of HAZ and the lack of filling in the stirring zone becomes the problem, leading to the formation of cavity defects. It can be seen from Figs. 5(B)-(D).

### *6.2 Microstructures analysis*

Fig. 6 presents the detailed microstructures of A356 and C355 aluminium alloys joint after friction stir welding. In the friction stir welding, mainly two-phase confluction is produced, HAZ and TMAZ. Affected thermally and mechanically at different degrees, microstructures in these two zones are composed of grains with different structures. As shown in Figs. 6(C) and (D), the transition from the HAZ to the TMAZ is sharp. During the FSW process, the sub-size concave shoulder cause intense plastic material flow in the HAZ. The TMAZ is the result of the thermal effect and the plastic shear stress caused by the plastic material flow in the HAZ, thus grains in this zone are appreciably elongated along the direction of maximum shear stress. As HAZ is affected by both the sub-size concave shoulder and the rotating tool pin. Because of the experienced high temperature and intense plastic deformation, microstructures in the HAZ are characterized by fine and equaxied grains, which are formed according to the dynamic recrystallization mechanism (Figs. 6(C) and (D)). HAZ also experiences high temperature and intense plastic deformation caused by intense stirring effect of the rotating tool pin, and microstructures in this zone are also characterized by fine and equaxied grain structures owing to the dynamic recrystallization mechanism which is a usual phenomenon when affected by high temperature and intense plastic deformation (Figs. 6(A) and (B)).

Table 6. Analysis of variance (ANOVA) for tensile strength.

| Source | Sum of square | DF | Mean square | F value | Prob. > F |
|---|---|---|---|---|---|
| Model | 73719.67 | 9 | 8191.07 | 133.72 | < 0.0001 |
| A (axial force) | 14450.00 | 1 | 14450.0 | 235.89 | < 0.0001 |
| B (welding speed) | 14450.00 | 1 | 14450.0 | 235.89 | < 0.0001 |
| C (rotational speed) | 33800.00 | 1 | 33800.0 | 551.77 | < 0.0001 |
| AB | 400.00 | 1 | 400.00 | 6.53 | 0.0378 |
| AC | 400.00 | 1 | 400.00 | 6.53 | 0.0378 |
| BC | 2500.00 | 1 | 2500.00 | 40.81 | 0.0004 |
| $A^2$ | 4020.25 | 1 | 4020.25 | 65.63 | < 0.0001 |
| $B^2$ | 500.25 | 1 | 500.25 | 8.17 | 0.0244 |
| $C^2$ | 3565.52 | 1 | 3565.52 | 58.21 | 0.0001 |
| Residual | 428.80 | 7 | 61.26 | | |
| Lack of fit | 300.00 | 3 | 100.00 | 3.11 | 0.1511 |
| Pure error | 128.80 | 4 | 32.20 | | |
| Cor total | 74148.47 | 16 | | | |
| Std. dev. | 7.83 | | R-Square | | 0.9942 |
| Mean | 229.18 | | Adj-R squared | | 0.9868 |
| C.V. | 3.42 | | Pred R-squared | | 0.9326 |
| Press | 5001.25 | | Adeq precision | | 36.650 |

### *6.3 Analysis of tensile strength*

Tensile strength plays an important role in determining the welding strength of the weld plates (C355+A356). Welding of alloys by FSW dependent on many factors, it is more influenced by parameters like axial force, welding speed and tool rotational speed etc.

The selected experimental design is box behnken design and the design matrix is shown in Table 5. The analysis of response was done using design expert software. Analysis of variance for Tensile strength shown in Table 6. Values of "Prob>F" are less than 0.0500 indicate that model terms are significant. From the Table 6, linear terms axial force, welding speed, rotational speed, square terms of axial force, welding speed, rotational speed and interaction terms between parameters are significant model terms. Values are greater than 0.10 indicate that model terms are not significant. If input parameters (axial force, welding speed, and tool rotational speed) contribution with respect to tensile strength is fit, then p value is less than 0.05 and significance of corresponding term is established.

$$\text{Tensile strength} = -8418.70000 - 139.70000 * \text{Axial force} - 18.64400 * \text{Welding speed} + 20.88800 * \text{Rotation speed} + 0.40000 * \text{Axial force} * \text{Welding speed} - 0.20000 * \text{Axial Force} * \text{Rotation speed} + 0.02000 * \text{Welding speed} * \text{Rotation speed} + 30.90000 * \text{Axial force}^2 + 0.017440 * \text{Welding speed}^2 - 0.011640 * \text{Rotation speed}^2 . \quad (3)$$

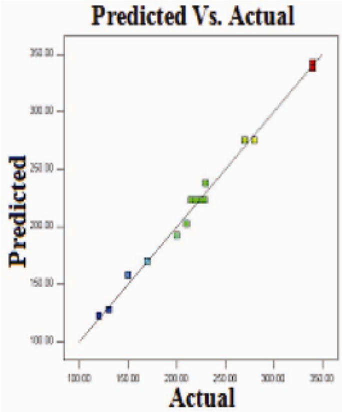


Fig. 7. Correlation between the predicted and actual values.

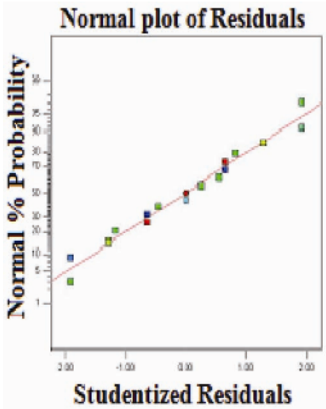


Fig. 8. The normal probability of residuals.

Analysis of variance (ANOVA) technique was used to check the adequacy of the developed empirical relationship. In this investigation, the desired level of confidence was considered to be 95%. The model F value of 133.72 implies that the model is significant. There is only a 0.01% chance that a model F value this large could occur due to noise. The lack of fit F value of 3.11 implies that the lack of fit is insignificant. There is only a 15.11% chance that a lack of fit F value this large could occur due to noise.

The goodness of fit of the model was checked by the determination coefficient ($R^2$). The coefficient of determination ($R^2$) was calculated to be 0.9942 for response. This implies that 99.42% of experimental data confirms the compatibility with the data predicted by the model. The $R^2$ value is always between 0 and 1, and its value indicates correctness of the model. For a good statistical model, $R^2$ value should be close to 1.0. The adjusted $R^2$ value reconstructs the expression with the significant terms. The value of the adjusted determination coefficient (Adj $R^2 = 0.9868$) is also high to advocate for a high significance of the model. The Pred $R^2$ is 0.9326 that implies that the model could explain 95% of the variability in predicting new observations. This is in reasonable agreement with the Adj $R^2$ of 0.9868. The value of coefficient of variation is also low as 3.42 indicates that the deviations between experimental and predicted values are low. Adeq precision measures the signal to noise ratio. A ratio greater than 4 is desirable. In this investigation, the ratio is 36.65, which indicates an adequate signal.

Fig. 7 shows the correlation between the predicted and experimental values for Tensile strength. The normal probabilities of residuals are shown in Fig. 8. After the regression model of surface roughness was developed, the model adequacy checking was performed in order to verify that the underlying assumption of regression analysis is not violated. Fig. 8 illustrates the normal probability plot of the residual which shows no sign of the violation since each point in the plot follows a straight line pattern. The normal probability plot is used to verify the normality assumption. The data are spread

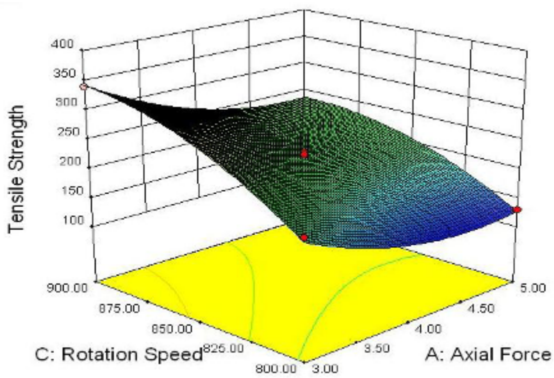


Fig. 9. 3D relation between Rotation speed, axial force and tensile strength.

roughly along the straight line. Hence, it is concluded that the data are normally distributed.

### *6.4 Effect of process parameters on tensile strength*

The influence of friction stir welding process parameters like axial force, welding speed and tool rotational speed, were evaluated against tensile strength of welded tensile pieces alloys (C355+A356).

#### *6.4.1 Effect of axial force on tensile strength*

The axial force is monitored through a load sensor and torque by the current and voltage from the servo motor. Fig. 9 show the influence of axial force on the tensile strength of A356 and C355 aluminium alloys joint. The formation of the defective welds can also be related to this. It has been found from Fig. 9 that, with an increase in axial force, the tensile strength decrease. It was observed in the present work, that the defective welds are formed at higher axial force (5/KN) and at lower axial force (3/KN), defect-free welds are formed. The axial force and torque requirement is substantial during welding and hence defect-free welds are formed beyond a critical limit. With an increase in heat input, the contact area below

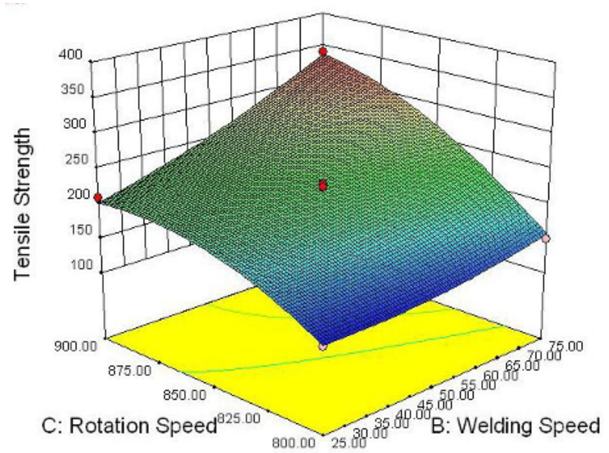


Fig. 10. 3D relation between rotation speed, welding speed and tensile strength.

the shoulder area or stir zone becomes softer, resulting in reduced strength in this region. The tensile strength will not be large, if defective welds are formed. For good-quality welds without internal defects, lesser axial force and torque is recommended.

#### *6.4.2 Effect of welding speed on tensile strength*

The effect of variation in welding speeds (50 to 75 mm/min) on the tensile strength is evaluated as shown in Fig. 10. The defective welds are observed at lower welding speed (25 mm/min). It was observed that an opposite effect is seen while increasing the welding speed as compared to axial force. By increasing the welding speed, the tensile strength is increased. Once sufficient welding speed (75 mm/min) is reached, defect-free welds are generated. This suggests that, for defect-free welds, higher welding speeds generating higher tensile strength is recommended. With an increase in welding speed, heat input decreases, resulting in higher strength at stir zone. For a stronger stir zone, leading to an increase in the magnitude of tensile strength at joint.

#### *6.4.3 Effect of tool rotation speed on tensile strength*

The tensile strength, welding speeds and tool rotational speeds are plotted in Fig. 10 for variable tool rotational speed. It was observed that tensile strength at lower tool rotational speed (800 RPM) is lesser, whereas at higher tool rotational speed (900 RPM) is higher. It means that, with an increase tool rotational speed, the tensile strength increases. In friction stir welding, tool rotation speed results in stirring and mixing of material around the rotating pin which in turn increase the temperature of the metal. It appears to be the most significant process variable since it tends to influence the transitional velocity. It is known that the maximum temperature was observed to be a strong function of rotation speed. When the rotational speed increases, the heat input within the stirred zone also increases due to the higher friction heat which in turn result in more intense stirring and mixing of materials.

Table 7. Confirmation result.

| Response | Prediction | Std. Dev. | SE (n = 1) | 95% PI low | 95% PI high |
|---|---|---|---|---|---|
| Tensile strength | 223.2 | 7.82669 | 8.57371 | 202.926 | 243.474 |

By analyzing the tensile strength, the average achievable predicted tensile strength is found to be 223.2 MPa. Importance of process parameters can be ranked from their F ratio which is mentioned in Table 6. It can be concluded that tool rotational speed is contributing more and it is followed by axial force and and welding speed.

## 7. Conclusions

The following conclusions can be drawn from the analysis;

(1) It was found from the analysis that, within the welding parameters range chosen, lower axial force (3/KN), higher welding speed (75 mm/min.), and higher tool rotational speed (900 RPM) are preferred for producing a weld without internal defects.

(2) Within the welding parameters range, tensile strength of weld (C355+A356) decreases, by increasing the axial force while by increasing the welding speed and tool rotational speed from minimum to maximum limit, the tensile strength of C355 and A356 aluminium alloys joint increases.

(3) Based on analysis of variance (ANOVA), Axial force, welding speed, and tool rotational speed were found to be suitable for tensile strength with regression p-value less than 0.05 and lack of fit more than 0.05.

(4) Within the welding parameters range, It was found that the parameters which affect the tensile strength in descending order are as follows: tool rotational speed, axial force and welding speed.

(5) An empirical relationship was developed to predict the tensile strength incorporating welding parameters at 95% confidence level. The predicted value for tensile strength was found 223.2 MPa.

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