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Investigation of friction welding parameters of AISI 304L/Ti-6AL-4V joints

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Abstract

The present paper focuses on evaluating the bonding strength interfaces between the contact materials such as AISI 304L and Ti-6Al-4V via the friction welding (FW). Experimental tests are performed by considering the process parameters such as friction time, rotational speed and friction pressure, mechanical properties were evaluated. The rotational speed of 1800, 1600, 2100, 2300 and 2500 rpm were considered in the study. The response surface methodology (RSM) is used to predict the outcomes of the work. Experimental tests were revealed that the friction pressure of 160 MPa, 7 sec of friction time and speed of 2300rpm are the optimal parameters based on the joint strength. Also, observed that the aluminum interlayer thickness of 1.25 μm on the Ti-6Al-4V side and 1.38 μm on the AISI 304L side. The tensile strength of 143.39 MPa was noticed at the interface area. The RSM response generates the curved potential line frequency range with 6.5% elongations. Results confirm that, the response surface methodology outcomes and experimental values were in close agreement.

1. Introduction

Solid state joining process such as friction welding, friction stir welding, etc. in which considerable heat is created on the facing surfaces of two components using a specific combination of pressure, duration, speed, and weld face surface roughness. Friction generates heat, which softens the materials to be bonded before plastically deforming them. Following the plasticization of an interfacial area, a metallurgical bond is established under the action of axial forging force due to relative movement [1, 2]. Balasubramanian et al [3] explained the new method of friction welding of dissimilar materials titanium to stainless steel. Anand Rao et al [4] investigated the friction welded titanium/SS304L (austenitic) dissimilar joints for their properties. The study clearly revealed that, the materials parameters such as upset time, rotational speed and forging pressure haven’t created many changes in the material properties of the friction welded titanium/SS304L, and noticed brittle fracture interfaces between the joint structures. Optimum parameters such as rotational speed 1500 rpm and 2000 rpm, with friction pressure 116 Mpa, upset pressure 193 MPa with 5 mm and 6 mm of burn of length it show good strength of about 216MPa. Nikhil Gotawala et al [5] analyzed the variation of thickness and structure on properties at Al 6061/Mild steel interface. Alex Anandaraj et al [6] studied the effect of parameters on friction welded dissimilar joining of Inconel 718 and AISI 410 martensitic stainless steel. The weld failure was noticed in both a weld

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interface and TMAZ, which may be due to the martensite and intermetallic formation. Tao et al. studied the fracture toughness of dissimilar titanium alloys joined by friction welding. It was clearly observed that, when temperature increases gradually from 585 °C to 700 °C, the fracture morphology of welded zone transforms from intergranular fracture to ductile-brittle mixed fracture and dimple fracture with increasing fracture toughness. Caimei Wang et al. joined TA15 and TC17 titanium alloys using friction welding, studied the properties. The TC17 side welding zone (WZ) was composed of coarse $\beta$ phases, $\alpha$ phase at grain boundaries and martensite $\alpha'$ phase at the grain interior, while the TA15 side WZ consisted of abundant acicular martensite $\alpha'$ phases and few retained $\beta$ phases. Cheepu et al. examined the joint interface characteristics and properties of dissimilar friction welding titanium/304 austenitic stainless steel with aluminum as insert layer, successfully.

Investigators were observed that the formations of brittle phases were effectively precluded with aluminum interlayer, absence of reaction compounds and brittle phases ensued the drastic improvement in the properties of the joints. Hardik D. Vyas et al. measured the properties of continuous drive friction welded dissimilar materials Copper-Stainless steel pipe joints. Superior interatomic diffusion was revealed which is leading to enhancement of metallurgical bonding for weld joined by 15s friction time. The reaction layer thickness of 17.28 $\mu$m & 1.21 $\mu$m was observed for the weld made by friction time of 10 s & 15 s respectively. Serdar Mercan et al. studied the welding parameters effect on fatigue properties of friction welded dissimilar AISI 2205/AISI 1020. Dey et al. investigated dissimilar metal joint of titanium/SS 304L, which results in a stronger weld in which failure occurs in the Ti base metal during tensile testing. However, the joints have almost zero bend ductility that has been attributed to the formation of intermetallic due to mechanical alloying, strain hardening of Ti near the joint interface and residual stresses. Muralimohan Cheepu et al. welded titanium/304 stainless steel with interlayer (electroplated nickel coating), which prevents the formation of brittle intermetallic phase. Results revealed the Ti-Ni intermetallics layers at weld interface on titanium side, noticed higher hardness at this location and the brittle fracture failure was occurred at the intermetallic layer. The maximum strength of 242 MPa and 308 MPa, were recorded for 30 $\mu$m and 50 $\mu$m thick electroplated nickel interlayers respectively. Kumar et al. joined dissimilar materials such as Ti-6Al-4V and SS304L by friction welding using interlayer techniques. Joint tensile strength of 523 MPa was noticed at a friction pressure of 12 N mm$^{-2}$, upset pressure of 40 N mm$^{-2}$, friction time of 1.2s and upset time of 7s. Muralimohan Cheepu et al. produced joints between stainless steel and titanium, in order to prevent the brittle intermetallic compounds formation. These aluminum inserts improves the weld interface metallurgical reaction at interface. Huihong Liu et al. welded Ti-6Al-4V alloy with SUS316L using friction welding. Joints were showed hard and brittle Ti64/SUS316L mechanically mixed layers at the weld interface. This may be because of high temperature, high rotation linear velocity & outward flow velocity of Ti-6Al-4V. These layers introduce cracks in the interface, impairing the strength. Kumar et al. investigated properties of friction stir welded dissimilar Ti–6Al–4V and SS304L materials, while welding interlayer i. e. oxygen free copper was utilized to produce defect free sound joints. Lourdes D. Bobbio et al. investigated Ti-6Al-4V to 304L stainless steel, immediately introduced V to proclude the formation of Fe–Ti Phases. Addition of V resulted in cracking, which was due to the formation of brittle $\alpha$-FeV. Won Bae Lee et al. studied the properties of the friction welded Ti/AISI 321 stainless steel, ultimate tensile strength of about 420 MPa was recorded with the conditions of upset pressure of 400 MPa and friction time of 0.5s. Yi Di Gao et al. investigated on friction welded TC4 Ti alloy to 304 stainless steel, interlayer of TA2/Q235 was used to prevent the formation of brittle Ti–Fe intermetallics at the interface. Shanjeevi et al. studied joints of stainless steel 304L and EN14 steel, factorial design was developed and performed with control parameters such as friction pressure, upset pressure, burn-off length and rotational speed. Results showed that low friction pressure at higher burn off length and high speed results in increased tensile strength. Jeong-Won Choi et al. investigated the influence of the applied pressure and frequency on the microstructure and mechanical properties of the friction welded Ti-6Al-4V alloy joint. At low applied pressure, practically the interfacial temperature crosses the $\beta$-phase transformation temperature, results in $\alpha$-lamella structure inside the recrystallized $\beta$-grains. On the other hand, at high applied pressure, the interfacial temperature was lower than the $\beta$-phase transformation temperature, which resulted in the $\alpha$-equiaxed grains. Higher applied pressure resulted in the higher vickers hardness at the interfacial region due to refined recrystallized grains. But good tensile property with the superior elongation was resulted regardless of the processing parameters since there is no softening region in the obtained joints. Mukundhan et al. studied the effect of forging pressure on microstructure and tensile properties of Friction Welded Ti64 joints. The study reveals that wider interface is observed for lower forging pressure and decrease with raise in forging pressure. The tensile strength increases with increase in forging pressure and it gradually decreases over increasing the forging pressure. Alex Anandaraj et al. studied the influence of rotary friction welding process parameters on dissimilar joining of Inconel 718 and AISI 410 steel. The welded joints were failed in both weld interface and thermo mechanical affected zone, because of the formation of martensite and intermetallic structure. Also noticed that the joint strength decreased with an increase in the operating temperature.
Thanikodi et al [25] carried out an experimental study on friction stir welding (FSW) of AA8006. The goal of their study was to determine the level of process variables for FSW AA8006 in order to minimize variability using the experimental approach of trial and error and minimize the number of samples that need to be characterized in order to optimize the process parameters. The ideal process parameters are proposed based on the results. In another work, Thanikodi et al [26] increased the strength and corrosion resistance of an aluminum alloy hybrid matrix mechanically. The process parameters for the mechanical and corrosion tests were optimized using a L9 OA statistical analysis. They found that the wear and micro hardness test were significantly influenced by the reinforcing percentage, but the ultimate tensile strength was significantly influenced by the stirring time parameter. Thanikodi et al [27] focused on the optimization of feed (0.15, 0.20, and 0.25 mm/rev), speed (800, 1200, and 1600 rpm), and cutting depth (1.0, 1.5, and 2.0 mm) when turning aluminium alloy 7075 in a CNC machine. They found that the L27 array Taguchi approach enhanced the outcomes in terms of material removal rate (highest), surface roughness after machining (lowest), and cutting force (least amount).

Literature clearly shows that the bonding strength is more likely affected by friction welding process parameters such as friction time, rotational speed and friction pressure etc. In this present study, an attempt has been made to evaluate the bonding strength of AISI 304L and Ti-6Al-4V dissimilar materials friction welded joint considering a range of the friction time, rotational speed and friction pressure. Further, it was analyzed by response surface methodology and compared with experimental results.

2. Experimental details

Friction welding technique is adopted to join the dissimilar metals of AISI 304L and Ti-6Al-4V, their chemical compositions and mechanical properties are shown in tables 1 and 2 respectively. The welding parameters and design approaches were given in table 3. The friction welding machine (capacity of the continuous driving load is 60 tons) is used in the study. Circular cross-section work pieces are used in both samples, and diameters are followed by 100 mm length and diameter is 18 mm. prior to weld, the adjoined surfaces of both the materials are
cleared by acetone. The stainless steel is mounted on the rotating chuck, and titanium alloys is at the non-
rotating side. The rotor rotated at high revolution speed and produced high contact pressure with the machining
interfaces.

The plastic deformation is reached the high-temperature distributions from the machining parameters.
Hence it derives the machine's heating time is 5 s certainly, aluminum is getting plasticized during frictional contact. It quickly
contacts both end-side material particles with good interface behaviors. The rotational speed intervals are
performed in the manufacturing process like 1800 rpm, 1600 rpm, 2100 rpm, 2300 rpm, and 2500 rpm,
respectively are used. The friction pressure is continuously performed in the manufacturing process like 40
MPa to 60 MPa, respectively. In the welded samples, burn lengths are identified 5 mm to 6 mm, and taken
friction time is 5 s.

A step-by-step procedure followed during friction welding is demonstrated in figure 1. Initially work
materials of Ti-6Al-4V and AISI 304L, out of which one is being rotating element, were mounted in the machine
collets, (b) slight forging pressure is applied (c) the upset time is allowed (d) the bulged shape joint interfaces developed,
completes the friction weld. Machining parameters and manufacturing methods
are shown the suitable bulged shapes of welded samples with contact areas. In the welded contact elements are
proved the better performances of mechanical characteristics. The positioning of the materials during friction
welding as shown in figure 2. Figure 3 shows the friction welded joints. It is noticed that the aluminum particles
are bonded only in Ti-6Al-4V. On the AISI 304L alloys side, nothing had happened in bonding. So the
manufacturing parameters have been changed and verified the results predict the good molecular strengths
shown in the AISI 304L side. The speed and upset pressure variants determined the heat generations. Large
diameters of dissimilar joints did not create a significant difference in the intermetallic joints. Therefore, Al alloy
is presumed to have a good bonding connection around the Ti/Al interface. The growth of Al interface is
gradually increase upon machine running.

Tensile test on friction welded specimens was conducted, test specimen as per the standard dimensions
mentioned in section IX of American Society of Mechanical Engineers (ASME) standards, as shown in
figure 4(a). For the tensile testing, 1.5 mm min\(^{-1}\) cross head travel speed is used, and the test is performed using
universal Testing Machine (average loading capacity is 60 kN). Optical microscopy is performed using an
Olympus microscope (model: BX53 M), the samples are processed according to the standard metallurgical

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Steps involved in Friction welding process (a) two materials, out of which one is being rotating element, were mounted in the
machine collets, (b) slight forging pressure is applied (c) the upset time is allowed (d) the bulged shape joint interfaces developed,
completes the friction weld.
The microhardness test was done using hardness measurement tester. Randomly three locations were selected on each specimen for hardness measurements, shown in figure 4(b).

**Figure 2.** Schematic view of the positioning of the materials during friction welding.

**Figure 3.** Friction welded samples.
3. Result & discussion

3.1. Mechanical behavior

Figure 5(a) is shown the maximum ultimate results from the tensile characteristics and stress-strain relationships. The heat flow method of stress-strain rate is identified the mechanical behaviors. Hence, figure 5(b) predetermined the load versus displacements results from the parent materials. Figure 5(c) demonstrate the load versus displacement relation at friction stirred zone, and tensile results showed in the down peak simulation. The curved potential line is acted down in the frequency range of showed 6.5% elongations. Figure 5(d) shows the stress-strain relationship of down peak ranges of tensile results and determined the low impact stress values. High strength friction welded samples of tensile results are shown in figure 5(e). It rectified the low strength interface bonded results and shown the low impact results of the joints. Maximum displacement is achieved from figure 5(e), shown 5.5 mm. Upset pressure welding joints results are shown the figure 5(f). The results have shown the 143.39 MPa of maximum tensile rates of interface areas.

Vickers micro hardness testing was done on the developed friction weld interface structures. The welded samples were cut at 2 mm from the mid joint areas. Hence, it is derived from the properties of chemical reactions and thermal behaviors. The micro hardness results are shown manufacturing defects and zero contact effects. Hardness measurements were done on five different samples, three different locations in each sample with constant load of 0.5kg. Figure 6 shows the micro hardness measurements for the samples. The maximum values of hardness results are shown from the stainless steel to aluminum interfaces. Hardness values on sample 1 at three different locations are found to be 325, 340 and 338 HV. The location two and three results are almost the same in all the different locations. The samples 3 & 4 derived the low impact range of 310 MPa.

3.2. Microstructure evaluation

The microstructure method has developed the process of machining results and deviations. Initially, the test samples were polished by the nital solutions. The microstructure machine tested the finely etched samples. Figure 7(a) represents the evaluations of Ti-6Al-4V/AISI 304L interface reactions and mechanical characteristics. The α ferrite particles are observed from the interface cracked areas. The 400 μm range of depth interfaces were analyzed and evaluated. Figure 7(b) shows the shapes of the equiaxed grains from the 200 μm range of depth. D90 brass structures formed in interfaces of aluminum and stainless steel contacts. Figure 7(c) shows the H90 Brass shapes in Titanium to aluminum particles. It was taken from the depth range of 150 μm. They witness the good molecular strengths and less corrosion properties. Three layered bonded combination results are shown as in below figure 7(d). AISI 304L, aluminum and mixed of Ti-6AL-4V bonded relationship are shown as good contacts & mechanical strengths. Three layered bonded interference results were analyzed from the 150 μm depth range.

It was observed the microstructure evaluations from the bonded interference of Ti-6Al-4V/AISI 304L. The metallurgical characteristics were deeply investigated from the experimental method. The machining parameters and mechanical properties results were compared with microstructure evaluations. These results are shown good molecular behaviors from the manufacturing processes. Hence, figure 8 shows the micrographs of the joint interference. Figure 8(a) represents the high interference energy locations of (10−5−15) joint molecular behaviors. It was analyzed in the depth of 10 μm range. Figure 8(b) is shown the medium interface energy locations (5−15−10) in the welded regions. This investigation represents the sufficient heat transferred from the machining setups. The evaluation results identified the good strength behaviors and structures. The wave interference appeared in the less interference joint locations (15−10−5) and showed in figure 8(c). This wave frequency is mainly adopted from the aluminum side contacts [30]. Figure 8(d) is shown the axial direction of...
high impact molecular behaviors and less corrosion rates. The welded machining samples results are predicted good bonding strength and shown suitable metallurgical surfaces. Microstructure analysis reveals irregular shapes of the morphological surfaces, layer of decarburized cracks were formed. Dark grey colour appeared in mixing aluminum particles into dissimilar samples. H90 brass particles which were highlighted in the morphology, controls the cracks initiated by the welding.

3.3. Optimization parameters and design variables
The design parameters are located as the optimization variables for significant characteristics and variables. The physical geometry parameters determined the friction surfaces and regression analysis of coated samples. The ANOVA simulations analyze manufacturing parameters. 2\(^{3}\) design factorial method is achieved the process replications for design experts. The Response Surface Methodology (RSM) analyzed the exact contact bondings and design parameter results. In the RSM is helped to finding the contact relationship between the

Figure 5. Welded joints Tensile results (a) stress matrix on Heat Flow Weld (HFW) zone (b) Parent materials of Ti-6Al-4V/AISI 304L (c) Friction Stirred (FS) interface joints Correlation (d) EB Relationships (e) High Speed (HS) tensile results (f) Upset pressure (UP) interface Relationship.
RSM is identified the molecular bonding behaviors and the different number of trial results \cite{31,32}. The desirability controlled results are predicted the better replications of ANOVA performances, represented in equations (1) & (2).

Figure 6. Micro hardness performances of Ti-6AL-4V/AISI 304L in Friction welding.

Figure 7. Microstructures of Ti-6AL-4V/AISI 304L analysis (a) α-Ferrite interferences (b) D90 Brass units locations (c) H90 Brass traces with high SS locations (d) Ti-6AL-4V/AISI 304L joint interface behaviors.
Table 4. ANOVA performances for different response sample results.

| Trials | Friction Pressure | Friction Time | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Desirability | Remarks |
|--------|-------------------|---------------|----------|----------|----------|----------|----------|--------------|---------|
| 1      | 190.000           | 10.000        | 592.751  | 774.870  | 302.246  | 201.171  | 195.970  | 0.946        |         |
| 2      | 189.797           | 10.000        | 592.668  | 773.140  | 302.172  | 200.966  | 195.735  | 0.944        |         |
| 3      | 189.612           | 10.000        | 592.593  | 771.573  | 302.105  | 200.780  | 195.235  | 0.942        |         |
| 4      | 190.000           | 9.930         | 590.325  | 775.074  | 300.560  | 199.871  | 194.848  | 0.939        |         |
| 5      | 190.000           | 9.835         | 587.052  | 775.352  | 298.286  | 198.117  | 193.335  | 0.930        | Selected |
| 6      | 188.116           | 10.000        | 591.984  | 758.846  | 301.563  | 199.269  | 193.797  | 0.929        |         |
| 7      | 190.000           | 9.810         | 586.169  | 775.427  | 297.673  | 197.644  | 192.927  | 0.928        |         |
| 8      | 190.000           | 9.697         | 582.271  | 773.756  | 294.963  | 195.355  | 191.125  | 0.917        |         |
| 9      | 185.661           | 10.000        | 590.983  | 737.971  | 300.674  | 196.791  | 190.967  | 0.906        |         |

Table 5. ANOVA results for performances.

| Source            | Sum of Squares | dof | Mean Square | F-value | p-value | Remarks       |
|-------------------|----------------|-----|-------------|---------|---------|---------------|
| Model             | 3.869E + 05    | 3   | 1.290E + 05 | 92.77   | <0.0001 | significant   |
| A                 | 3748.32        | 1   | 3748.32     | 2.70    | 0.1265  |               |
| B                 | 12162.43       | 1   | 12162.43    | 8.75    | 0.0120  |               |
| AB                | 11179.77       | 1   | 11179.77    | 8.04    | 0.0150  |               |
| Residual          | 16681.07       | 12  | 1390.09     |         |         |               |
| Absence of Acceptable | 13768.48   | 5   | 2753.70     | 6.62    | 0.0139  | significant   |
| Uncontaminated Error | 2912.59     | 7   | 416.08      |         |         |               |
| Cor results       | 4.036E + 05    | 15  |             |         |         |               |

Actual Factor = $-1007.81 + 5.63027 \times \text{Friction Pressure} + 124.124 \times \text{Friction Time} - 0.52681 \times \text{Friction Pressure} \times \text{Friction Time}$  
(1)
The above factors derived the design variable equations and proved the significant relationships for friction coated. The least-square method was adopted the response values from the computational models. Hence, the actual and predicted results are identified as the P-values of statistical results and maximize the surface responses. These experimental results are derived from three phases of parameter and five response variables of different samples. Upper limits and lower limits variations are determined through the ANOVA performances. The significant effects of significant P-values represent the selected materials with multi-response behaviors. The response results are identified the rotational speed with statistical results. Multi response characteristics and co-efficient of P-values are determined in the ANOVA performances. The co-efficient correlation results appear in the P-values of statistical

Figure 9. Perturbation results for ANOVA performances in Ti-6Al-4V/AISI 304L.

Figure 10. Standard design error results performed in friction pressure and friction time.

Predicted Factor = $-3061.27 + 17.4112 \times \text{Friction Pressure} + 357.662 \times \text{Friction Time} - 1.70039 \times \text{Friction Pressure} \times \text{Friction Time}$  (2)

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Figure 11. Predicted versus actual residual plots results (a) normal probability versus residual stresses (b) Sample 1 results of predicted versus actual comparisons (c) Sample 2 results of predicted versus actual comparisons (d) Sample 3 results of predicted versus actual comparisons (e) Sample 4 results of predicted versus actual comparisons (f) Sample 2 results of predicted versus actual comparisons.
results. The ANOVA equations represent the transverse speed of rotational moments in different responses. The method two results are shown the low transverse speed and low rotation rpm performed results are shown good bonded strengths and responses. The effective bonded materials are identified from the optimization processes.

Rotational speed and axial load performance results are determined through the ANOVA table. Table 4 shows the experimental results and manufacturing data from the different response conditions. The average friction pressure 190 MPa is identified from the ANOVA table. The friction time average limit is identified from table 4, shown 9.835 s. Different response samples averages like 587.052, 775.352, 298.286, 198.117 and 193.335. From the nine different ANOVA tests, the fifth trial samples results are good as from all. The desirability average ratio representation value is 0.930. These tests are selected from the ANOVA table and represent the good strength of manufacturing behaviors.

Table 5 is shown average Fishers value of 92.77 implies results are represented. The predicted result indicates 0.01% of high noise is produced during the manufacturing process. The residual performances are shown significant models in acceptable rates. In the significant models are derived the A & B residuals. In the determined residual mean square value is 16681.07 safe in the design process. Corrosion resistance values represent the 4.036E +05 in safe bonding conditions. In the manufacturing experiment, data is shown in table 5. The uncontaminated errors are denotes 416.08 percentage in the manufacturing process. Here, it is 1.39% of
chances for acting vibrations in the manufacturing conditions. The significant parameter combination is good for manufacturing process and also noise levels are very less in the process. The Perturbation graphs represent the five different samples results from the response surface. AB residual points indicate the optimized value for the Perturbation method. Figure 9 is shown the value of the coded units of 2000 rpm power generated from the parameter controls. A & B point plots are indicated the position of response areas from the ANOVA performances. Sample 1 Perturbation results identified the friction pressure range of 450 to 580 MPa and closely maintained the 2000 rpm for the rotational speed. Sample 2 Perturbation results are shown in the variation friction pressure ranges. It identified 450 to 800 MPa with 2000 rpm speed. Sample 3 identified 200 to 300 MPa with 2000 rpm speed. Sample 4 indicated 130 to 160 MPa with 2000 rpm speed. Sample 5 indicated 140 to 150 MPa with 2000 rpm speed. Hence, deviation and Perturbation results are displayed in figure 9.

ANOVA performances predict the standard design errors from the design of experiments. Friction pressure and standard design error represent the 170 to 180 MPa friction pressure is transformed into all response surfaces. In this pressure, range results are shown good molecular bond from the manufacturing processes. In the same way, friction time and standard error design represent the 7 to 8 s of the experimental samples provide better resolutions of strengths. Figure 10 represents the standard error designs are exhibits the good ANOVA performances from the manufacturing products.

No constant variation results and process parameters are performed in figure 11. Probability and residual rates of comparison are shown the better results of experimental tests. The experimental and theoretical results are compared and identified the closeness values in figure 11(a). The safe values are predicted in the results. Figure 11(b) is shown the sample 1 performance results are compared to predicted results. It indicates a few of the tests are merged with predicted results. Figure 11(c) is shown the non-continues, and medium variational results are represented. The gap is identified by the peak variations of the continuous trial results. Figure 11(d) is shown the continuous trial results and the wide range of residual values predicted. The deviation of the flow is represented from the graphical forms. Figure 11(e) is shown the sample 4 tests continuous and no variation results. The comparison results and graphical model is shown in figure 11(e). The trial five samples performances and manufactured parameter setups are evaluated and investigated in figure 11(f). The comparison results of actual and predicted results are shown the no variance passed in the experimental setups.

Mean plot effects represent the optimization parameters and performances of machining controls. In particular, Friction pressure, friction time, and residual speed locations indicate the standard mean plots from the Minitab performances. Figure 12 is shown the mean plot effect deviations for data means. Figure 13 is shown the residual plot

Figure 14. XRD results of welded Ti-6AL-4V/AISI 304L joints (a) Welding interferences of D90 Brass and Steel (b) Deviation of grain structures (c) Recrystallization region with parent locations (d) Plastic strain variations with welding interferences.
responded for fixed variance and optimal orders for different tests. The complicated design structures are shown the peak values and intervals for the interference behaviors. Frequency and observed order indicate the good bonded structures and welded shapes.

Interface results and manufacturing parameters are identified in figure 14. The vibrational peak performances have deviated from the three different layers. Figure 14(a) is shown the interface behaviors from the D60 steel to H90 brass. The elements of the peak variances are shown good molecular strengths and controls. Hence, the grain and deformed regions plot deviates are shown from the parent materials. The peak structures are also representing in figure 14(b). Recrystallization and grain regions are varied from the parent structures. Figure 14(c) is shown the peak

Figure 15. (a) is shown three dimensional RSM Results for design parameters figure 15 (b)–(f) shown the five different samples and different parameter results.
variations performances by the changing of position angles. Plastic strain rates and welded interface results are represented in figure 14(d). The deformed regions and brass performances are shown good contact behaviors representing in the experimental setups.

Figure 15(a) is shown the overlay plots for different kinds of residual stresses and joint behaviors are representing. Design expert's solutions make the overall optimization techniques and detailed bonding efficiency. 150 to 160 MPa ranges of friction pressure and 6 to 10 s of friction time are performed in all experimental methods. Figure 15(b) is shown the 6 s of friction time and 150 MPa of friction pressure combinations getting good bulged shapes in the machining process [33, 34]. Figure 15(c) is shown the 7 s of friction time and 160 MPa of friction pressure combinations getting a good bonded effect in the machining process. Figure 15(d) represents the deformed shapes and contact behaviors of the welded areas. Figure 15(e & f) commonly shows the contact surfaces and molecular behaviors of the interference strengths and structures.

4. Conclusions

With the help of Friction welding, Ti-6AL-4V/AISI 304L joints were produced, the interface behaviors of contact surfaces were also defined successfully. The parametric studies and experimental technique results were drawn and discussed in the previous section were summarized as follows:

1. The constant study parameters and influence variable regions are analyzed between the interlayer surface reactions. Mixed aluminum particles to titanium and stainless steel results of microstructure evaluations were compared to previous research works.

2. Friction pressure and standard design error represent 170 to 180 MPa friction pressure is transformed into all response surfaces. Perturbation result is identified from the friction pressure range of 450 to 580 MPa for the rotational speed of 2000 rpm.

3. The residual result is determined by the residual mean square value of 16681.07 which is safe in the design process evaluation. Experimental and manufacturing parameters derived the 9.835 s responses friction pressures like 587.052, 775.352, 298.286, 198.117 and 193.335 MPa.

4. The ANOVA represented the transverse speed of rotational moments in different responses. The RSM showed the curved potential line frequency range with 6.5% elongations and maximum displacement of about 5.5 mm higher responses were achieved. The maximum tensile strength of about 143.39 MPa was recorded at the intermetallic bonded regions between titanium and stainless steel.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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