 Rotary friction welded C45 to 16NiCr6 steel rods: statistical optimization coupled to mechanical and microstructure approaches

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Abstract
In the present work, the dissimilar joints between C45 carbon steel and nickel-chromium 16NiCr6 steel rods were produced using rotary friction welding process. Statistical analysis based on response surface methodology (RSM), microstructural examination using scanning electron microscopy with backscattered electron diffraction (EBSD) and mechanical tests were performed to investigate the friction weld joints. The results showed that friction time and rotation speed were the most effective parameters on the weld joint quality with the highest t-ratio of -4.27, where the maximum bending strength of 1406.9 MPa was obtained at 2000 rpm for 13 s friction time. Increasing friction time to 13 s resulted in remarkable decrease in grain size (about 35%) at the weld interface, which increased the hardness (350HV0.1) and elastic modulus (260 GPa).

Keywords Rotary friction welding · RSM methodology · Microstructure

1 Introduction
Welding is often the weak point of these joint structures, especially if they are subjected to shock or vibratory loads. Some of these dissimilar joints require the use of input metals, and relatively expensive and difficult welding techniques. Most represent deficits in resistance to mechanical stresses caused by the melting of metals, which induces the brittleness of the weld bead [1–4]. Medium carbon steels have average or poor weldability, although their very diverse use in the construction industry is because of their high mechanical strength. C45 and 16NiCr6 quality steels are extended and used in various industrial applications such as shipbuilding and the automotive industry. In fact, rotary friction welding (RFW) allows similar and dissimilar joints to be produced, which is a solution for obtaining high welded joints [5–8]. Hence, RFW is used for the produce vehicle parts such as drive shafts, engine valves, pumps and compressor [9].

RFW creates joining by elevation of the temperature between the two surfaces in contact under effect of rotation speed and pressure; one of the pieces is held in the stationary part, at the same time, the other is chuck in moving part, the two pieces being in contact of each other until the rotation stopped rapidly; this period is called friction phase. The pressure amplified to terminate the process and finish of welding joint, this period of time is called forge phase [10]. This technique has several advantages: the absence of smoke and sparks, no filler metal, no shielding gas, a high welding rate for a short welding time, excellent mechanics, metallurgical properties and a very resistant weld joint [8]. Contact between the two parts will trigger a flash, which will remove impurities and oxides from the interface, which will subsequently promote the creation of a weld with excellent chemical and physical properties [7]. Thus, the thermally affected zone (TAZ) will expand to a lower thickness in friction welding than conventional welding [11].
Numerous research works on RFW and their parameters have been forgotten through experimental and analytical methods to optimize favorable welding conditions. The basic parameters of RFW are rotational speed \( V \) (rpm), friction time (s), friction pressure (MPa), forging time (s) and forging pressure (MPa). Table 1 presents a literature review for some of the previous authors operating conditions in RFW.

For optimizing friction welding parameters, there are two methods for optimizing these parameters. The first one depends on a single factor, changing one condition and fixing the others, while the second relies on the statistical method [19]. Several researchers used a design of experiments approach (DOE) in different applications [20–23], including a response surface methodology (RSM), when many parameters influence response or more responses of interest.

However, Akbar Heidarzadeh [24] used the response surface methodology of RSM for friction-stir welding. The results show that the most effective parameters for joint elongation and strength were tool rotation, force and forging force, respectively. Optimization of these parameters showed that the maximum elongation of 55% and strength of 318 MPa can be achieved at a rotational speed of 1000 rpm, advance speed of 58 mm/min and an axial force of 03 kN. S.T. Selvamani and K. Palanikumar [25] have performed RSM on the production of AISI 1035 carbon steel rods to optimize RFW parameters and achieve maximum tensile strength. The ANOVA method showed that a maximum expected tensile strength of 548 MPa could be achieved under welding conditions of 1464 rpm rotational speed, 03 s friction time, 86 MPa friction pressure, 03 s forging time with 86 MPa forging pressure. On the other hand, some works have studied RFWs of steels, similar and dissimilar joints [26–28].

Based on our knowledge, there is limited study in open literature that reports the use of design of experiments and especially the full factorial approach to investigate the influence of parameters to measure the ultimate bending strength (UBS) using a proper experimental design of carbon steel C45 with nickel-chromium alloy steel 16NiCr6 which improves the ultimate bending strength (UBS) of welded joint in first place. And provide the best clarification of the origins of the improvement in mechanical performance. Subsequently, the materials were characterized and evaluated by microstructural and mechanical behaviour changes in RFW parameters using optical microscope (OM), SEM, electron backscatter diffraction (EBSD) its effect on most significant parameter of welded joint.

### 2 Experimental procedures

Medium carbon steel (C45) and Nickel chromium alloy structural steel for case hardening (16NiCr6) rods with 12 mm in diameters and 45 mm in length were used for the present study. The chemical compositions and mechanical properties of the base metals are presented in Tables 2 and 3, respectively. The microstructure of the C45 and 16NiCr6 showed both a ferrite and pearlite structure with a difference in proportion. Welding operations were performed using the RFW machine with maximum rotational speeds up to 3000 rpm and maximum pressure of 300 MPa. C45 test piece was fixed in the rotary side, while the 16NiCr6 steel was kept in stationary one. Design of experiments approach was conducted to simultaneously optimize the levels of the working parameters in order to obtain the best system performance. It is a set of statistical and mathematical techniques that work by fitting a polynomial system equation to experimental data, which describes the behaviour of a set of data in order to make statistical predictions [19]. The following independently

| Ref | Materials          | \( D \) (mm) | \( V \) (Rpm) | \( P_{\text{friction}} \) (MPa) | \( P_{\text{forging}} \) (MPa) | Friction time (s) | Forging time (s) |
|-----|--------------------|--------------|---------------|-------------------------------|-------------------------------|-------------------|------------------|
| [12] | SUS304-SUS304      | 25           | 500-900-1500  | 60-80-100                     | *                             | 0.2 to 15         | *                |
| [13] | 304SS-304SS        | 25           | 1500          | 80                            | 80                            | *                 | 6                |
| [11] | AISI 1040-AISI 1040| 10-12        | 2095          | *                             | *                             | 16-18             | *                |
| [8]  | AISI 1010-ASTM B22 | 20           | 2500          | 20                            | 22                            | 1-8               | *                |
| [14] | AISI 304L-4340 steel | 12           | 1500 to 2500  | 40                            | 60                            | 5                 | *                |
| [7]  | AA1050-AISI304     | 14.8         | 3200          | 2.1                           | 1.4                           | 7-32              | 2                |
| [15] | AISI 304-AISI 1060 | 20           | 2000          | 30-40-50                      | 50-70                         | 5                 | *                |
| [16] | AISI 316-AISI 304  | 12           | 3000          | 130                           | 260                           | 6.5-8.5-10        | 5                |
| [17] | AISI 316-AISI 316  | 12           | 3000          | 130                           | *                             | 6.5-8.5-10        | *                |
| [18] | AISI 304-AISI 304  | 12           | 3000          | 130                           | 260                           | 6.5-8.5-10        | 5                |

- \( D \): sample diameter
- \( N \): rotation speed in road per minute
- *: information not mentioned by the authors
controllable process parameters were identified for the experiments: friction pressure (F), friction time (T) and rotational speed (V). Constant forging pressure (70 MPa) and forging time (3 s) are used in this study. The working ranges of all the selected parameters were determined by carrying out tests. One of the parameters was modified, while the others were kept at constant values. The working range of each welding parameter was determined by checking that the weld was free of visible defects. For experimental design, JMP 13 software with ANOVA methods was used, where the upper and lower limits with different levels of the identified process parameters are shown in Table 4. The selected design matrix is a central composite factorial design consisting of 16 sets of coded conditions [29]. All friction welding variables at the intermediate level (0) are the centre points and combinations of each of the welding variables at their lowest (−1) or highest (+1) level.

After welding, a flash of metal is observed for all specimens, as shown in Fig. 1; this indicated that the surfaces of the joined materials were softened and plastically deformed; hence, their solid-state welding has occurred [30]. This behaviour could occur due to increased temperature induced by the elevation of friction time which softened the steel and favoured its plastic deformation. Figure 1a shows a view of welds from different parameters used present RSM model. The weld joints show similar macroscopic aspects with different flash formation sizes as the welding parameters change from minimum to maximum units. Figure 1b shows an example of the flash formation after welding process; this behaviour in rotary friction welding come when an increase in parameters and the generated heat, which was higher at the periphery than in the central area of the welded joint [31].

The bending tests of the friction weld joints were conducted according to ASME BPVC Section IX-2017 (QW160). The samples were cut perpendicularly to the weld line with geometry of 40 mm (length), 6 mm (width) and 3 mm (thickness) as schematically illustrated in Fig. 1c. Bending tests were conducted on TIRA test 2300 machine with a bending rate of 1 mm/min and automatically stopped at 8 mm of bending. It is notable that five bending tests were carried out for each FRW parameters. The 16 experimental runs allowed for the friction welding parameters combination, the experimental and predicted ultimate bending strength (UBS) and the graphs are summarized in Table 5 and Fig. 2, respectively.

The microstructure of the joints was first examined by using an optical microscope (OM). The OM sample was sectioned from the joints parallel to the direction of welding Fig. 1d, and then prepared by mechanical polishing until using OPS 0.04 μm; chemical etching was done with a solution of 1 ml nitric acid in 100 ml ethanol. SEM and EDX ZEISS Gemini SEM 300 were used to observing the fractured surfaces. For EBSD used a SEM Jel JSM 7000F on two samples S3 (00-1) and S11 (00+1) were prepared by ionic polishing to study the evolution of the grain structure.

Nano-indentation measurements were done by Anton Paar NHT-3 nano-indentor with a Berkovich tip using a 50 mN applied load. The indenters were carried out in the welding centre, while the hardness and Young’s modulus were automatically calculated taking into account the standards of the instrumented indentation using the Oliver-Pharr method [32]. Scratch tests were carried out on Bruker UMT equipment, across the welding interface at a constant load of 20 N with a scratch length of 10 mm and a speed of 0.1 mm/s. While Vickers micro hardness HV 0.1 measurements have been performed by WILSON VH3300 machine along the transvers section of the friction weld joints. A filiation of 70 points with 0.3 mm path has been selected starting from C45 side towards the 16NiCr6 steel in the middle of the cross section.

### Table 2 Chemical composition of the base metals (wt%)

| Material   | C    | Mn  | Si  | P     | S     | Ni  | Cr   |
|------------|------|-----|-----|-------|-------|-----|------|
| C45        | 0.45–0.50 | 0.7 | 0.3 | <0.035 | <0.035 | –  | –   |
| 16NiCr6    | 0.14–0.17 | 0.15–0.40 | 0.40–0.60 | –     | –     | 1.40–1.70 | 1.40–1.70 |

### Table 3 Mechanical properties of the base metals

| Material | HV 0.1 (°) | Rm(N/mm²) | Re(N/mm²) | A % |
|----------|------------|-----------|-----------|-----|
| C45      | 180–210    | 560–620   | 275–340   | 14–16 |
| 16NiCr6  | 200–230    | 650–1400  | 470–800   | 9–11  |

### Table 4 Factors and levels used in the study

| Parameter                  | Notation | Unit  | Factor levels |
|----------------------------|----------|-------|---------------|
| Rotation speed (X₁)        | V        | rpm   | 2000 2500 3000 |
| Friction pressure (X₂)     | F        | MPa   | 20 30 40     |
| Friction time (X₃)         | T        | s     | 9 11 13      |
3 Results and discussions

3.1 Factorial design of experiments

3.1.1 Model fitting

The evaluation of effective process variables on the UBS (MPa) was performed based on the composite central design (CCD) matrix with two replicated points. The design points, experimental and predicted results of (UBS) are represented in Table 5. The 16 experimental tests were performed in a random sequence to minimize the effects of uncontrolled factors; the first attempt consisted on fitting the experimental response UBS directly with a second order (polynomial) model (Eq. 2). The present study has found that the relationship between ultimate bending strength (UBS) of the friction welded samples joints is a function of the friction welding parameters such as rotational speed ($X_1$), friction pressure ($X_2$), and friction time ($X_3$) which can be expressed as [25]:

$$UBS = \{X_1; X_2; X_3\}$$

(1)

The second-order polynomial equation is used to represent the response surface ultimate bending strength given by:

$$UBS = b_0 + \sum b_i X_i + \sum b_{ij} X_i^2 + \sum b_{ij} X_i X_j$$

(2)

For three factors, the chosen polynomial model can be expressed as:

$$UBS = b_0 + b_1 (X_1) + b_2 (X_2) + b_3 (X_3) + b_{12} (X_1 X_2) + b_{13} (X_1 X_3) + b_{23} (X_2 X_3) + b_{11} (X_1^2) + b_{22} (X_2^2) + b_{33} (X_3^2)$$

(3)

where ($b_0$) is the average of the responses and $b_1, b_2, b_3...b_{33}$ are regression coefficients [33] that depend on the respective
Table 5  Design layout including experimental and predicted values

| No | Samples | $X_1$ | $X_2$ | $X_3$ | Experimental (MPa) | Predicted (MPa) | Crack |
|----|---------|-------|-------|-------|--------------------|-----------------|-------|
| 1  | S10     | 1     | -1    | -1    | 1295              | 1288.50862     |       |
| 2  | S6      | -1    | 1     | -1    | 1109              | 1096.80862     |       |
| 3  | S8      | 0     | 1     | 0     | 1144              | 1165.16552     |       |
| 4  | S4      | 0     | 0     | 0     | 1202              | 1223.06897     |       |
| 5  | S5      | -1    | 0     | 0     | 1267              | 1245.16552     |       |
| 6  | S16     | 1     | 0     | 0     | 1302              | 1311.76552     |       |
| 7  | S1      | -1    | -1    | -1    | 1134              | 1145.90862     |       |
| 8  | S3      | 0     | 0     | -1    | 1158              | 1174.36552     |       |
| 9  | S7      | 1     | 1     | -1    | 1265              | 1255.40862     | *     |
| 10 | S14     | 1     | -1    | 1     | 1358              | 1373.20862     |       |
| 11 | S2      | 0     | 0     | 0     | 1220              | 1223.06897     |       |
| 12 | S15     | -1    | 1     | 1     | 1323              | 1332.50862     |       |
| 13 | S12     | -1    | -1    | 1     | 1386              | 1398.60862     |       |
| 14 | S13     | 0     | -1    | 0     | 1248              | 1214.76552     |       |
| 15 | S9      | 1     | 1     | 1     | 1332              | 1323.10862     |       |
| 16 | S11     | 0     | 0     | 1     | 1363              | 1334.56552     | *     |

*There was a fracture of the sample

Fig. 2  Load-displacement curves for bending test for all samples, a S1-S4, b S5-S8, c S9-S12 and d S13-S16
linear, interactive and squared terms of the factors. The significance of each coefficient is determined by 'F' and 'p' values, listed in Table 6.

The value of the coefficient is calculated using the Design Expert Software. The quadratic model proved to be adequate for predicting the response given by the following equations:

\[
\text{UBS (MPa)} = 1223.06 + 33.3X_1 - 24.8X_2 + 80.1X_3 + 4X_1X_2 - 42X_1X_3 - 4.25X_2X_3 + 55.39X_1^2 - 33.1X_2^2 + 31.39X_3^2
\]

Equation (4) can show the interactions between variables. They have significant effects on the response; the results are therefore presented and discussed. The statistical significance of Eq. (4) is presented in Table 7. From Table 6, respectively, the terms mean square, degree of freedom (15) and sum of squares are defined as the variance estimation of the model, the number models, and the total sum of squares for model.

The ANOVA (F test) shows that the second-order model (quadratic polynomial) also corresponds to the experimental data. The p value is a quantitative measure to report the result of a hypothesis test. This is the probability that the statistical test is at least as extreme as those observed, since the null hypothesis is true. Based on the results of Fig. 3, \( R^2 \) was equal to 0.96 indicating the model to satisfy the response well [25]. Table 5 shows the difference between the experimental and predicted values; it is easy to deduce that the results are close to and less than 5% which is a good indicator of the quality of the results. This result and tendency were relatively similar to the work cited in the literature [34].

The degree of freedom (15) in Table 6 indicates the total number of model terms, including the intercept minus one. It is clearly that the model is highly significant, as suggested by the model F value (15.9716) and a low probability value (p value = 0.0016). If p value is less than or equal to the chosen significance level alpha value of 0.05, the test suggests that the observed data are inconsistent with the null hypothesis. Therefore, it must be rejected and the factor effect is significant [35]. It appears from Table 7 that the linear effects of rotation speed, friction pressure and time are significant. The same trend was observed for the interaction effects between these factors, which confirms that the model is highly significant with the p value of 0.0016 < 0.05 [36-38] and F value of 15.9716 cited in ANOVA analysis in Table 6. The results obtained are in line with the approaches used in the literature [39, 40].

The current study have analyzed the results obtained, which appear in the Table 7; it can be concluded that friction time \( X_3 \) was the most important parameter for the overall UBS (MPa) with a high t-ratio: 9.11; the parameter exerts a stronger influence on the response (UBS). Second, rotation speed was the second important influencer parameter phenomenon with a t-ratio: 3.79. Friction pressure was the least significant parameter with a t-ratio: 0.41. The negative sign means that the factors and the response are inversely proportional.

The difference between experimental and predicted values is illustrated on UBS in Fig. 4. There are points below and above straight line called point of line zero; the positive values observed on the residual plot show a low predictive result. While

| Table 6 | ANOVA analysis of UBS (MPa) |
|---------|-----------------------------|
| Source  | Sum of squares | \( D_f \) | Mean square | \( F \) ration | p value |
| Model   | 111129.13       | 9       | 12347.7     | 15.9716       | 0.0016*  |
| Error   | 4638.62         | 6       | 773.1       |               |          |
| C.Total | 115767.75       | 15      |             |               |          |

*\( p < 0.05 \)

\( R^2 = 0.96 \)
negative values imply that the prediction was high, a value of zero means that the prediction is accurate since there is a total superposition between experimental and predicted values. The residual plot for UBS following Eq. (4) shows a random pattern; this indicates that the distribution of residuals for the response approximately follows the fitted normal distribution.

3.1.2 Interaction plots

Figure 5 illustrates possible positive and negative effects of two variables interactions, respectively, among the three parameters on UBS response. The non-parallel curves show an interaction that can be estimated between rotation speed ‘\( X_1 \)’ and friction time ‘\( X_3 \)’ equal to 0.0052, so the higher values of rotation speed affect UBS capacity when friction time is high and equal to 9 s.

In addition, the effects of interactions such as rotation speed ‘\( X_1 \)’ and friction pressure ‘\( X_2 \)’, friction pressure ‘\( X_2 \)’ and friction time ‘\( X_3 \)’ are negligible due to parallel curves, which indicate the friction pressure \( X_2 \) is the least significant or non-significant in the presence of other parameters simultaneously. These results confirm the previous finding obtained from Table 7, related to each parameter of influence on UBS process. Consequently, and to better understand the relationship between the three variables studied and the response related to UBS, a cubic graph is presented in Fig. 6.

The cubic graph demonstrates that increasing rotation speed \( V \) from 2000 to 3000 rpm and friction pressure from 20 to 40 MPa considerably decreases UBS from 1288.51 to 1145 MPa and 1288.51 to 1255.41 MPa. The absence of parameter input of \( X_2 \) (friction pressure) and speed of rotation of \( X_1 \) on the weld joint could be explained in the survey. Consequences of an increase in two previously located parameters influence the increase in the welded joint resistance until it reaches its limit and decreases again. The reason is increased plastic deformation resulting from excessive pressure and rotational speed [7].

3.1.3 Response surface methodology

To further illustrate and discuss the effect of each factor and the interactions between these factors, we were referred to the

![Image](image-url)

Fig. 4  Residual plot of Ultimate bending strength UBS in MPa in the model

![Image](image-url)

Fig. 5 Interaction effect plots of the UBS (MPa) vs. studied parameters
3D response surface plots which were drawn as three-dimensional plots of two factors. In contrast, the other factor was kept constant. The 3-dimentional response surface for UBS (MPa) is shown in Fig. 7.

Figure 7a represents UBS for different values of rotation speed \((X_1)\) and friction pressure \((X_2)\) for a constant friction time \((X_3)\). It is clearly that the response (UBS) increases when friction pressure \((X_2)\) increases independently. Figure 7b illustrates the combined effect of rotation speed \((X_1)\) and friction time \((X_3)\) for a constant value of friction pressure \((X_2)\) on UBS response. It can be seen that UBS increases as friction time \((X_3)\) decreases at friction pressure values. Therefore, Fig. 7c shows the effect of friction pressure \((X_2)\) and friction time \((X_3)\) on UBS at the constant value of rotation speed \((X_1)\). It can be seen that at high values of friction time \(t\), UBS increases independently. As reported in previous work [15], hardness and tensile strength are increased with increasing friction time. Those are influenced by the augmentation of the young’s modulus and the impact of friction time on the welded joint, which is also recognized in the micro-structural observation.

Figure 7 indicates UBS optimization results which can be achieved at lower rotation speed values \((X_1)\).

### 3.1.4 Optimal design conditions using the desirability method

The main object of this study was to find the optimal conditions in which UBS will be maximized. Suich and Derringer well used that desirability function in 1980 to solve the problems related to the optimization of industry-related multiple responses which have been applied in many studies [41–43]. Figure 8 illustrates the prediction profiler function of the studied parameter; it can be concluded that optimized conditions were rotation speed of 2000 rpm, friction pressure of 24.77 MPa and friction time of 13 s for a predicted response UBS of 1406.892 MPa with a desirability value of 0.991859.

### 3.2 Experimental results

#### 3.2.1 Micrographic and metallographic analysis

Figure 9 shows an optical micrograph of welded joint for different zones, thermal-affected zones (TAZ) and thermo-mechanical affected zones (TMAZ) shown in Fig. 9; the welded joints were perfectly bonded; no cracks, low pores and no defect are observed. The grains are different in each affected zone, mainly resulting from temperature and pressure distribution variation. The grains are not uniform, elongated in the TAZ as shown in Fig. 9a and c, and refined in TMAZ as shown in Fig. 9d and f, cause of pressure application and heat due to thermo-mechanical action [26]. Furthermore, a reduction in ferrite and pearlite rate in each in steels is observed compared to the base metals [25]. Ferrite/pearlite ratio remained the same in both steels after welding, i.e. the proportion of ferrite is predominant in C45, and conversely the rate of pearlite is higher in 16NiCr6.
Two flows are observed in the vicinity of the welded joint (Fig. 9b and e); the connection line of two steels plays the role of an inverse axis of symmetry. Noticed also that the existence of continuity enrolls the absence of interface within a good junction between the samples; the grain size has decreased significantly compared to TMAZ, which is a direct consequence of dynamic recrystallization (DRZ) of the grains [14, 44]. Indeed, the welding zone consists of equiaxed grains because sufficient DRZ is occurred [45].

Figure 10 represents SEM and EDX analysis performed at the central region of the bonding interface at the welded joint ends. The results are similar, with little variation in diffusion layer between the main chemical elements of C45 and 16NiCr6 steel. Figure 10a reveals most relevant advantages of friction welding can be easily deduced. In fact, a significant reduction in the number of pores compared to base metals can be seen, probably a consequence of high plastic deformation [46]. Figure 10b shows inter-diffusion between Ni, Cr, Si and Mn, characterizing the diffusion as the primary bonding mechanism in the rotary friction welding process. The analysis records clearly diffusion of Cr and Ni through the interface from 16NiCr6 to C45. As a result of the diffusion, a gradual reduction of Cr and Ni in 16NiCr6 side adjacent to the interface and increasing of Cr and Ni in C45 side. Conversely is occurred for Si and Mn while these two last elements decrease in C45 interface side and increase in 16NiCr6 side; this result is in adequacy with references [7].

Figure 11 shows EBSD map of welded joint of two samples S3 (00-1) and S11 (00+1). The maps show red, green and blue colour which present 001, 011 and 111 planes respectively. It can be seen that the green colour dominates in the EBSD map for S3 welding parameters with low friction time and blue colour for S11 in high friction time (Fig. 11a and b respectively), which indicates that the grain orientation mainly
concentrates in the normal direction of crystallographic plane \( \{101\} \) for S3 and \( \{111\} \) for S11.

The grain size is not uniform for low parameters than for high parameters; no special high-density orientation distribution. The statistical result of grain indicates that the proportion of average diameter grain size is 3.32 μm in parameters with low friction time (00-1) and 2.15 μm for parameters with high friction time (00+1). The origin of finer grains in the high friction time input joint can be attributed to micro-structural evolution during RFW.

### 3.2.2 Mechanical behaviour

Figure 2 shows the curves of ultimate bending strength (UBS) of different welds with different experimental run. The minimum UBS obtained is 1109 MPa for weld S6 as observed in Fig. 2b and a maximum UBS of 1386 MPa for weld S12 as shown in Fig. 2c. This shows that there is variation in UBS with a change in parameters, and the influence of the most significant parameters (friction time) is clearly noticeable; in fact, an increase of almost 25% of UBS can be deduced from Table 5. Also, the curves show the two samples that cracked the most during the bending tests, namely samples 7 and 11 in Fig. 2b and c respectively.

Response surface methodology (RSM) study shows that the most significant parameter influencing UBS is friction time. In this perspective, the present work studied the mechanical behaviour of welded joint at the parameters of (00-1) (000) and (00+1), to demonstrate the contribution of friction time to weld joint behaviour. Valuable information’s on mechanical behaviour are provided using the measurements of hardness, wear and nano-indentation at different stages of the friction time.

Vickers micro-hardness distributions in specimens previously selected are shown in Fig. 12a. The measurements were carried out from C45 side to 16NiCr6 side. As expected, the micro-hardness reaches maximum values close to the interface and decreases very rapidly from TMZA until base metal. Figure 12a shows a comparison between welded specimens with high, low and medium friction time, as observed from this figure can recognize an increase of micro-hardness from \( t:9 \) s Hv 360 ± 10 to \( t:11 \) s Hv 430 ± 10 and then decrease in \( t:13 \) s to achieve Hv 350 ± 10 where the base metal on both C45 and 16NiCr6 were approximately Hv 200 ± 10 for C45 and
Hv 220 ± 10 for 16NiCr6; this increase may have caused by micro-structural evaluations around the interface, diffusion of elements on the sides, work hardening, dislocation and refinement of grains.

Similar hardness profile for the dissimilar material couple is reported in literature [6]. For 13 s friction time, the micro hardness values exhibit an increase of approximately 65% compared to the base metal, which is relatively lower.
compared to ones obtained using conventional welding processes [25]. The decrease in hardness at \( t: 13 \) s can be attributed to the decrease in temperature generated. In fact, after the plastic deformation, a reduction in friction is generally observed. The same behaviour has been seen in Fig. 12c. The nanindentation applied on the same samples shows a similar behaviour where the displacement into the surface at \( t: 11 \) s is less than those at \( t: 9 \) s and \( 13 \) s, which leads us to suppose that the hardness at \( 9 \) and \( 11 \) s friction time is similar.

Nevertheless, Fig. 12d shows a better understanding of the impact by increasing of welding time on mechanical behaviour. Notice that there is an apparent increase of young’s modulus of 260 GPa, compared to the lower friction times, \( t: 11 \) s is 210 GPa and \( t: 9 \) s is 230 GPa. Figure 12b illustrates three different scratch profiles. It can be seen at the interface with substrate various coefficient of friction with the change of welding time, also observed deep fluctuation in both C45 and 16NiCr6 sides that may be related to presence of the pores in those areas and can easily notice the decrease in these fluctuations at the weld interface, which maybe equates to decrease in that pores and confirms with Fig. 10a. Thus, close to the interface, a low deformation is observed due to the presence of TAZ, which reveals a high micro-hardness and that for all welded samples.

Regarding the behaviour as a function of friction time variation, notice that the friction coefficient decreases in the welded zone, which can be explained by high grains refinement. On the other hand, the variation of friction coefficient shows an increase at \( t: 11 \) s, which leads us to suppose that the grains have coalesced; this coefficient relapses at \( t: 13 \) s, due to grain disintegration formed after \( t: 11 \) s.

The fractured surfaces of the specimens S7 and S11 issued from bending tests are shown in Fig. 13. It can be seen that the fracture occurs in the C45 steel (rotary side) with elongated grain structure at fracture zone; the SEM observation indicates a river like pattern that commonly attributed to the brittle fracture [47]. The elongated structure at some region shows ductile fracture [27]. Figure 13a shows detailed view of the fracture surface in which the structure is elongated and dislocated, which is remarkable from one zone to another. Figure 13b and c illustrates that fracture surface for steels are with half bubbles or cups; the latter are characteristic of a ductile fracture and are formed by growth of cavities in the material. Ductile fracture is preceded by significant plastic deformation, often resulting in cups linked to decohesion around inclusions that act as the initiation of fracture. Fracture surfaces show the presence of several cups of sizes between 5 and 10 \( \mu \)m. These cups extend in the tensile direction. These cavities gather and coalesce in order to accelerate the fracture.

4 Conclusion

In this work, the impact of welding parameters (friction, time, friction pressure and rotational speed) of the microstructure evolution and mechanical response of the C45 /16NiCr6 steels obtained using rotary friction process is investigated using the statistical RSM technique. The main conclusions are summarized as follows:

- Friction time is the most effective parameter that individually affects the bending strength of the friction weld joints. However, considering the parameters interaction, rotational speed and friction time resulted in the highest UBS value of 1406 MPa.
- The results of bending test show a good accordance with the nano-indentation measurements where the higher mechanical properties are obtained in the friction weld joint using 2000rpm rotational speed and 13 s friction time.
- The higher the friction time, the finer the grain size and the higher the hardness and elastic modulus values.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article. The raw data that support the findings of this study are available upon a reasonable request.

Code availability Not applicable (jmp 13 design of experiments “free version”).

Declarations

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Consent to participate The authors state that the work was carried out in collaboration with all members.

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