Research and Test of the Self-Designed and Manufactured Rotary Friction Welding Machine with CT3 Steel Samples

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**Abstract.** This paper presents the results of research and test of the self-designed and manufactured rotary friction welding machine. Tensile test results show that the tensile strength of the material after welding is satisfactory according to the standards of the material; the elongation is within the elongation limit of the welding specimen; the yield limit is greater than the minimum yield limit of the material. The parameters of the welding equipment are guaranteed according to the design requirements.

**Introduction**

Friction welding is the welding method with the most stable and durable welded joint structure compared with the method of fusion welding of the material. In addition to the outstanding advantage in terms of ensuring the mechanical properties of the welded joint, an advantage that other welding methods cannot do is to connect different materials through the process of friction, the materials are diffused into each other. With rotary friction welding, when two parts rotate relative to each other, generating frictional heat that melts the material at the contact area, the two parts are pressed together to create a welded joint [1-3, 14-18], Fig. 1.

Fig. 1 Operating principle of rotary friction welding machine

In the 60s of the twentieth century, rotary friction welding developed strongly in the United States. Most of the equipment manufactured during this period was researched by AMF, Caterpillar, and Rockwell International companies [1-3]. Currently, rotary friction welding is strongly developed to meet the increasing needs of the manufacturing industry. At universities, a lot of research on rotary friction welding has been carried out in various aspects. Several in-depth studies on rotary friction have been carried out in the world. Researches on rotary friction welding machines: Gourav sardana and Ajay Lohan, have researched special fixture for friction welding on lathe machine [1]; Jagroop Singh, Karamdeep Singh, Department of Mechanical Engineering, ACEM, Kapur thala, Punjab, India have researched rotary friction welding on lathe machine with stallstock [2]; P. A. Thakare, Lt Randheer Singh designed and developed the micro rotary friction welding machine and investigated the friction welding parameters for similar materials [3]. Researches on welding of different materials...
includes: H. Ochi, working at Welding Research Center, Osaka Technical Research Institute, Japan, together with K. Ogawa studied the properties of the welds of aluminum alloy and steel. [27]; Z. Lindemann, K. Skalski, W. Wosinski, and J. Zimmerman studied the thermo-mechanical phenomenon in the process of friction welding of corundum ceramics and aluminum [14]; Eder Paduan Alves, Francisco Piorino Neto, Chen Ying An, Euclides Castorino da Silva conducted an experimental investigation of temperature during rotary friction welding of AA1050 aluminum with AISI 304 stainless steel [24]; M. B. Uday, M. N. Ahmad Fauzi, Zuhailawati H, A. B. Ismail of University of Materials and Mineral Resources Engineering, Malaysia, studied the effect of welding speed on the mechanical strength of friction welded joint of YSZ-Alumina composite and 6061 aluminum alloy [5]. Research on thermo-mechanical phenomena in the process of rotary friction welding includes authors with the following published work: Ruma Mohd Abdul Wahed, Mohammed Farhan studied the effect of external heating of the friction welded joint [17]; M. B. Uday, M. N. Ahmad Fauzi, Zuhailawati H, A. B. Ismail of University of Materials and Mineral Resources Engineering, Malaysia, studied the effect of welding speed on the mechanical strength of friction welded joint of YSZ-Alumina composite and 6061 aluminum alloy [5]. Jatinder Gill, Jagdev Singh experimentally studied the effect of heating time on the mechanical properties of nylon joints produced by friction welding [18]; Eder Paduan Alves, Chen Ying An conducted an experimental determination of temperature during rotary friction welding of dissimilar materials published in Scientific and Engineering Publishing Company [15]; Ali Moarrefzadeh studied the effect of heat in the friction welding process, published in Journal of Mechanical Engineering 2012 [16]. Evaluation of rotary friction welding includes the typical authors and works such as G. J. Baxter, M. Preuss and P. J. Withers at Manchester Institute of Natural Materials Research, UK, studied inertial friction welding of nickel base superalloys for aerospace applications [4]; Piaar Nagar, D. Ananthapadmanaban studied the friction weldability of low carbon steel with stainless steel and aluminum with copper [30]; P. Shiva Shankar, L. Suresh Kumar, N. Ravinder Reddy used Taguchi method to conduct an experimental investigation and analyze the friction welding parameters for Cu Zn28 copper alloy [6]; Amit Handa, Vikas Chawla made a review to evaluate friction welding [37]; Veerabhadrapra Algur1, Kabadi, Ganechari and Sharanasappana conducted an experimental investigation on friction characteristics of modified ZA-27 alloy using taguchi technique [7]; Amit Handa Punjub, Vikas Chawla Dav conducted an experimental study on mechanical properties of friction welded AISI 1021 steels [8]; Mumin Sahin and Cenk Misirli studied the mechanical and metallurgical properties of Friction Welded Aluminium Joints [31]; Ali. Moarrefzadeh performed a Numerical Modeling of Friction Welding Process [38]; The research team of Baiju Sasidharan, Dr. K. P. Narayanan, R. Arivazhakan studied the influence of interface surface geometries in the tensile characteristics of friction welded joints from aluminium alloys [20, 32].

Friction welding is one of the environmentally friendly welding methods. The main source of welding energy is the heat source due to friction between the contacting surfaces of the welding parts. This heat source causes the surface of the part to flow intensely in the structure of the material, a new feature in current biomechanical engineering. The welding principle is completely new, so it needs a lot of research from basic to in-depth. The material organization at the welded joints changes compared to the original material, and nanostructures can be achieved, which is very significant in the new materials industry. The requirement for experimental equipment is simple, and the theoretical basis encapsulated in mechanical engineering, which is very suitable for current research conditions in universities.

Models of Rotary Friction Welding Machines Designed and Manufactured

Based on the reference to the studies [1-3], [6-8] and the actual working conditions of the research team, after analyzing the options, an operating principle of the rotary friction welding machine was selected as Fig. 1, 2D design model as Fig. 2. Main parameters typical for welding process include: spindle rotation speed, friction pressure and friction time, forging pressure and forging time, upset length.
Fig. 2 2D design model of rotary friction welding machine

Fig. 2 and Fig. 3a show that when the rotation speed reaches a given speed $n$, hydraulic action causes two surfaces to rub against each other. Then the torque increases, and when the two frictional surfaces generate heat, the torque decreases. This stage is the friction phase. During the friction phase, the length of the workpiece is shortened by a small amount. When the friction surface has material overflow, the brake mechanism makes the rotation speed $n$ stop suddenly. During breaking the torque is maximum and the torque is zero when the rotation speed $n$ is zero. This is the braking phase. The braking phase takes place as quickly as possible (if the braking time is large, the heat reduction of the welded joint is limited). When the braking phase is about to end, the pressure should be increased so that the two surfaces diffuse intensely into each other. This stage is the forging phase. The steps to perform the rotary friction welding process are shown in Fig. 3b.

Fig. 3 Parameters and phases of rotary friction welding process

The rotary friction welding machine is manufactured (Fig. 4) fitted with a solenoid valve to control the hydraulic system (principle shown in Fig. 2).
Experiments

**Sample for experiment.** Test specimens of solid circular shape, with a diameter of 14 mm and a length of 100 mm, are made of CT3 steel with strength limits according to ГОCT 380 - 89 standard as shown in Table 1.

| Standard     | Mechanical properties |          |          |
|--------------|-----------------------|----------|----------|
| ГОCT 380 - 89| Yield limit (N/mm²)   | 225 min  |          |
|              | Tensile Strength (N/mm²) | 373 ÷ 461 |          |
|              | Elongation (%)        | 22 min   |          |

**Measuring instruments.** In the study, the CHT4106 universal tensile strength testing machine was used to measure the mechanical properties of the samples after rotary friction welding.

Fig. 5 HT4106 model universal compression tensile machine

HT4106 model universal compression tensile machine with load force of 1000kN, can perform tensile, compression, bending and cutting tests. Test standards are in accordance with ISO, ASTM, etc. With PowerTest software of SANS, all data and management are in the database, easy to access and transfer to other softwares such as Excel. Parameters such as yield limit, strength limit, relative elongation, elastic modulus, etc. can be measured or calculated automatically. The machine also determines the bending resistance of metal and can display 3 curves at the same time: stress-deformation, force-time, force-elongation of the test specimen.

**Experimental design.** Test parameters include: rotation speed of workpiece, friction force, friction time, forging time, forging force, upset length. In which, there are 2 fixed parameters (rotation speed of workpiece $n$, upset length $l$), 2 variable parameters that can be controlled (axial pressure in the friction stage $P_1$, axial pressure in the forging stage $P_2$) and 2 calculated dependent parameters: friction time $t_1$, forging time $t_2$.

**Table 2. Input parameters of the rotary friction welding test specimen**

| No | Axial pressure at stages | Symbol | Design variable value | Unit       |
|----|--------------------------|--------|-----------------------|------------|
|    |                          |        | Nature | Encode | (−1) | (0) | (+1) |          |
| 1  | Friction                | $P_1$  | A      |        | 50   | 70  | 90   | N/mm²    |
| 2  | Forging                 | $P_2$  | B      |        | 110  | 130 | 150  | N/mm²    |

The second-order symmetric mixed quadratic experimental planning of the form B with the polynomial regression equation has the general form as formula (1):
\[ y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_i x_i^2 \sum_{i<j} b_{ij} x_i x_j \]  

The study has chosen the second-order symmetric mixed planning of the form B, the experiment at the center of 2 to help keep the number of experiments to a minimum. Natural form planning matrix is shown in Table 3.

Table 3. Experimental planning matrix with input parameters

| Test specimen | \( n \) (rpm) | Axial pressing force | Time |
|---------------|--------------|---------------------|------|
|               | P1 (N/mm²)   | P2 (N/mm²)         | t1 (s) | t2 (s) | l (mm) |
| 1             | 50           | 110                | 50    | 7      | 4     |
| 2             | 90           | 110                | 36    | 7      | 4     |
| 3             | 50           | 150                | 50    | 5      | 4     |
| 4             | 90           | 150                | 36    | 5      | 4     |
| 5             | 50           | 130                | 50    | 6      | 4     |
| 6             | 90           | 130                | 36    | 6      | 4     |
| 7             | 70           | 110                | 43    | 7      | 4     |
| 8             | 70           | 150                | 43    | 5      | 4     |
| 9             | 70           | 130                | 43    | 6      | 4     |
| 10            | 70           | 130                | 43    | 6      | 4     |

Conducting experiments. The samples are cut to length and cleaned to remove oil, grease, etc. and ensure a flat, smooth, swarf-free work surface so that the two surfaces are in even contact, good friction, and faster heating time. 10 experiments with the same parameters are carried out as shown in Table 3 according to the basic stages: Friction process (Fig. 6) and Forging process (Fig. 7).

Results and Discussion

After the rotary friction welding equipment is manufactured and the above samples are tested, it shows that the friction welding equipment gets the set requirements: high rigidity, low vibration.
during operation, the main shaft motor ensuring the operating capacity and reaching the number of revolutions according to the design requirements, the sliding table mechanism operating smoothly and ensuring stability during the welding process, the hydraulic system ensuring the original design pressure.

According to the ASTM E8 standard, the samples after rotary friction welding (Fig. 8) are machined by turning method before the tensile test (Fig. 9). The sample after tensile test to determine mechanical properties is shown in Fig.10.

![Fig. 8 CT3 steel welding product](image)

![Fig. 9 Tensile test specimen according to ASTM E8 standard](image)

![Fig. 10 Sample after tensile test](image)

The number of repeated experiments of the planning was calculated and selected as 3. CHT4106 devices were used to measure the strength limit, yield limit and calculate the relative elongation with the results table as shown in Table 4.

| Test specimen | Tensile strength, $\overline{\sigma_b}$ (N/mm²) | Elongation, $\delta$ (%) | Yield limit, $\overline{\sigma_{0.2}}$ (N/mm²) |
|---------------|---------------------------------|-----------------|-----------------|
| 1             | 401.7                           | 16.7            | 281.6           |
| 2             | 401.7                           | 17.2            | 281.6           |
| 3             | 403.7                           | 17.1            | 284.2           |
| 4             | 407.9                           | 17.8            | 286.6           |
| 5             | 403.5                           | 16.9            | 283.7           |
| 6             | 407.2                           | 17.5            | 284.2           |
| 7             | 406.7                           | 16.9            | 281.8           |
| 8             | 405.6                           | 16.8            | 282.5           |
| 9             | 404.7                           | 16.3            | 281.2           |
| 10            | 404.2                           | 16.5            | 281.7           |

The relative elongation after break is calculated by the formula: $A = \left( \frac{L_u - L_0}{L_0} \right) \times 100$

The relative contractility is calculated by the formula: $Z = \left( \frac{S_0 - S_u}{S_0} \right) \times 100$

In which:

$L_0$: Initial session length.
$L_u$: Session length at the end
$L$: Total length of the original sample.
\( L_c \): Sample length at the end.
\( S_0 \): Original cross-sectional area of the parallel section.
\( L_u \): Minimum cross-sectional area after cutting.

**Tensile strength \( \sigma_b \).** Synthesis and analysis of parameters affecting tensile strength are shown in Table 5.

| Term       | Coef   | SE Coef | T-Value | P-Value |
|------------|--------|---------|---------|---------|
| Constant   | 405.150| 0.161   | 2511.87 | 0.000   |
| P1         | 1.061  | 0.132   | 8.06    | 0.000   |
| P2         | 0.867  | 0.132   | 6.58    | 0.000   |
| P1*P1      | -1.189 | 0.208   | -5.71   | 0.000   |
| P1*P2      | 0.692  | 0.161   | 4.29    | 0.000   |

The regression equation characterizing for the malfunction of the axial pressing force of friction and forging parts when welding friction can only be natural as follows:

\[
\sigma_b = 396.97 + 0.2444P1 - 0.0777P2 - 0.002972P1*P1 + 0.001729P1*P2
\]  
(2)

From here, graphs are built to show the influence of 2 input parameters on the tensile strength of the sample as shown in Fig. 11.

From the results of the analysis we realize that the higher the friction, the higher the strength, and when the maximum value is reached, it decreases. As the forging element increases, the tensile strength of the detail will increase steadily.
**Elongation δ.** Synthesis and analysis of parameters affecting elongation are shown in Table 6.

Table 6. Parameters affecting elongation

| Term     | Coef   | SE Coef | T-Value | P-Value |
|----------|--------|---------|---------|---------|
| Constant | 16.6024| 0.0548  | 303.02  | 0.000   |
| P1       | 0.3222 | 0.0374  | 8.61    | 0.000   |
| P2       | 0.1500 | 0.0374  | 4.01    | 0.000   |
| P1*P1    | 0.4119 | 0.0600  | 6.86    | 0.000   |
| P2*P2    | 0.1619 | 0.0600  | 2.70    | 0.012   |

The regression equation characterizing the influence of axial pressure of friction and forging parts when welding friction to the elongation of the sample of the natural form is as follows:

\[
\delta = 26.39 - 0.1281 P1 - 0.0977 P2 + 0.001030 P1*P1 + 0.000405 P2*P2
\]  

(3)

From here, graphs are built to show the influence of 2 input parameters on the elongation of the sample as shown in Fig 12.

From the results of the analysis, it is noticed that the higher the friction, the longer the elongation will decrease to the point of urination will increase. As the Forging factor increases, the elongation of the parts tends to increase but will initially decrease when it comes to the pole, which will gradually increase.

![Fig. 12 Elongation analysis results](image)

**Yield limit analysis σ_{0.2}.** Synthesis and analysis of parameters affecting yield limit analysis are shown in table 13.

Table 7. Parameters affecting the yield limit

| Term     | Coef   | SE Coef | T-Value | P-Value |
|----------|--------|---------|---------|---------|
| Constant | 281.558| 0.083   | 3407.21 | 0.000   |
| P1       | 0.6111 | 0.0675  | 9.06    | 0.000   |
| P2       | 1.3500 | 0.0675  | 20.01   | 0.000   |
| P1*P1    | 1.942  | 0.107   | 18.20   | 0.000   |
| P1*P2    | 0.2667 | 0.0826  | 3.23    | 0.003   |

The regression equation characterizing for the influence of axial pressing force of friction and forging parts when friction welding arrives yield limit analysis samples of natural form is as follows:

\[
\sigma_{0.2} = 300.50 - 0.7357 P1 + 0.0208 P2 + 0.004854 P1*P1 + 0.000667 P1*P2
\]  

(4)
From here, graphs are built to show the influence of 2 input parameters on yield limit analysis of the sample as shown in Fig. 13.

From the chart, it is noticed that the higher the friction, the lower yield limit. Especially, when it decreases to the minimized value, it tends to increase again. The more the forging factor increases, the yield limit increases.

Tensile test results with mechanical properties are synthesized and compared with the mechanical properties of the sample material (Table 1), with the table as shown in Table 8.

Table 8. Table comparing the properties of the welding specimen with that of the material

| Tensile strength (N/mm²) | Elongation (%) | Yield limit (N/mm²) |
|--------------------------|----------------|--------------------|
| Standard                 | Experiment     | Standard            | Experiment     | Standard | Experiment     |
| 373 ÷ 461               | 401.7÷407.9    | 22 min             | 16.3÷17.8      | 225 min  | 281.2÷286.6    |

Conclusion

The rotary friction welding machine has been successfully researched and manufactured, put to the test and achieved good results. The rotation speed of the part is stable and ensures the maximum number of revolutions required for friction welding is 1450 rpm. The hydraulic cylinder's propulsion mechanism is stable and generates pressure in accordance with the requirements of each material (160Mpa). The structure of the welding machine is firm, ensuring stability during operation. Transmission sliding table mechanism is smooth and stable. Materials with the same properties can be welded, meeting the set requirements.

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