Influence of Heating Stage Parameters on the Joint Strength of Rotary Friction Welded AISI 1045 and AISI 304 Steels: A Polynomial Model

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Abstract. Rotary friction welding (RFW) results is much affected by heating and joining stage parameters. Heating stage is the period where friction takes place to generate heat at the interface. Parameters that alter the heating are friction pressure, friction time and rotation speed. In this work, experiment of RFW AISI 1045 and AISI 304 under different friction pressure and friction time was carried out. The objective was to investigate the relation between those parameters with the welding strength. The experiments were performed using one-factor-at-a-time (OFAT) strategy. A polynomial model of relation between joint strength with friction pressure and friction time was developed. Welding efficiency of 81.7% from the AISI 304 base metal was attained. Optimum setting friction pressure of under constant friction time was 40 bar, whereas the optimum setting friction time under constant friction pressure was 5 seconds.

Introduction

Combination of dissimilar materials frequently required for mechanical components applications. These utilizations could incorporate beneficial properties of the materials. Fusion welding is difficult to join dissimilar materials due to the different properties which could be sensitive to the metallurgical change [1]. Brittle phase and cracking are common problems found in fusion welding of dissimilar materials [2]. Solid state welding such as rotary friction welding (RFW) can be proposed to solve problems in fusion welding of different materials. Joining below melting temperature in this technique yields lower heat affected zone than common fusion welding technique.

Although materials' joint could be produced under lower temperature (*i.e.,* below melting temperature), however problems of brittle intermetallic phase might still be faced in RFW. Therefore, proper parameters selection in the process should be considered to get good joint [3]. AISI 304 was successfully joined with aluminum using this technique. The joint strength was less than tensile strength of the aluminum [1]. This work found that friction pressure and upset pressure affected the joint and an optimum condition was indicated.

Influence of forging pressure on the mechanical properties of rotary friction welded AISI 1045 – AISI 316L has been explored [4]. Maximum welding efficiency of 90% was achieved at 75 MPa forging pressure. The study suggested that increasing forging pressure decreased tensile strength of the joint. Therefore, increasing the forging pressure above that value was not recommended. Increasing rotational speed was observed to improve tensile strength of AISI 304L [5]. The work argued that increasing heat plasticized material better and enabled full face contact which resulted in weld quality. Joining AISI 316 and AISI 316L stainless steel with copper produced joint strength that was higher than copper [6]. Higher tensile strength was given by combination of low friction pressure and high upset pressure.

The present research studied influence of heating stage parameters, *i.e.,* friction pressure and friction time on the joint strength of rotary friction welded AISI 1045 steel with AISI 304 stainless steel. Experiments were conducted varying the parameters while maintaining rotation speed, forging pressure, and forging time. Strength of the joint with respect to the changing parameters were investigated.

Experimental Procedure

Both materials (*i.e.,* AISI 1045 and AISI 304 steels) were supplied in round bar with diameter of 16 mm. Chemical compositions of the materials are given in Table 1. Prior to joining, the materials were cut into 120 mm length. The surface to be welded was turned to produce perfectly flat surface before joining process. Experiments of RFW process were performed following a procedure as shown in Fig. 1. While the friction pressure and friction time were varied; rotational speed, forging pressure, and forging time were maintained constant.

Table 1. Chemical composition of AISI 304 and AISI 1045 steels

	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Cu
AISI 304	0.063	0.36	1.11	0.032	0.008	18.09	8.11	-
AISI 1045	0.45	0.27	0.74	0.26	0.004	0.36	0.03	0.07

Step by step RFW procedures for the experiment is illustrated in Fig.1. One specimen was hold by rotating chuck that was attached to the spindle of lathe machine. Another specimen was gripped by the stationary chuck. The process was initiated with matching the surface of the specimen. It was followed by rotating the spindle and pushing the other specimen to make contact and friction between the materials' surface. Fluid control mechanism on the power pack system enables the equipment to adjust the friction pressure and the friction time. When the setting of pressure level and time were achieved, the spindle was stopped, and forging pressure was applied within the required time. Subsequently, the welded samples were machined to prepare the tensile test specimen according to standard of ASTM E8 (Fig. 2).

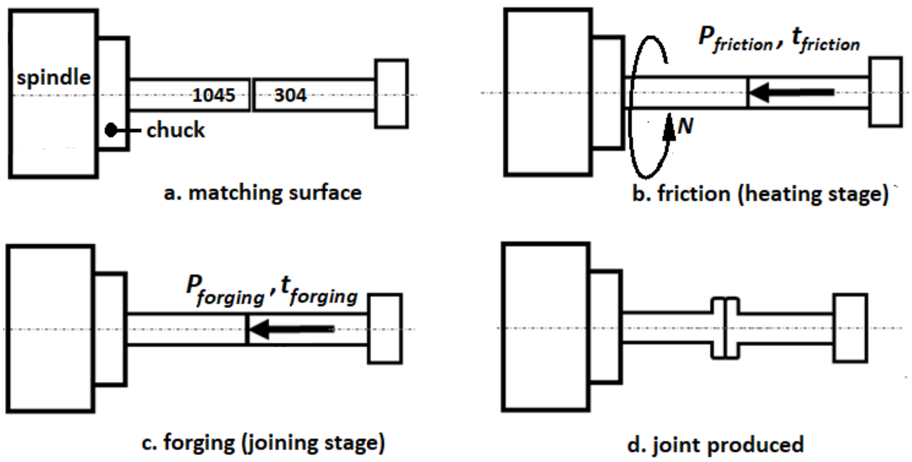


Fig. 1: Procedure of RFW experiments

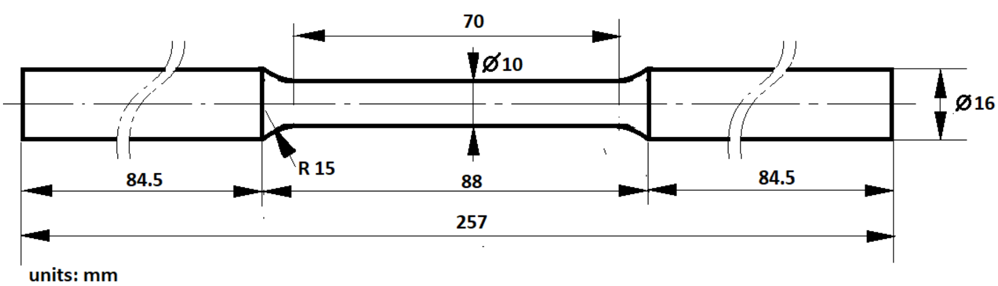


Fig. 2: Tensile test specimen based on ASTM E8 standard

Methodology

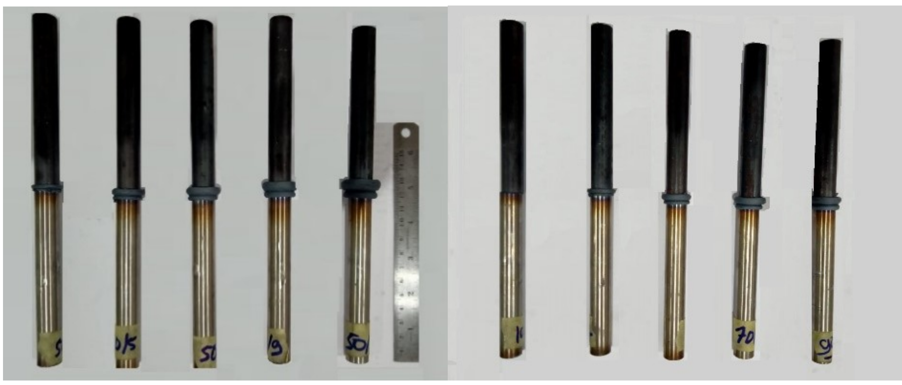
Pre-experiment. This research emphasizes exploration of two potential influencing factors in rotary friction welding of AISI 304 and AISI 1045 steels, *i.e.,* friction pressure and friction time. The choice of these two factors refers to the fact that the yield of friction welding depends on the parameter setting during heating process of welded material [7, 8]. It was also realized that there are other potential factors which influence the strength of joint metal, like forging pressure, spindle speed, and forging time. However, this research needs determine the gradual setting of friction pressure and friction time to capture the fluctuation of tensile strength accordingly while maintaining other factors constant.

Based on the works which have investigated hard-steel friction welding [7, 9], accepted setting for friction pressure is at around 10 to 100 bar. Meanwhile, friction time ranges between 3 to 13 seconds are logically accepted [7, 10]. A gradual change of these setting for each factor leads the experiment run to see their effect to tensile strength in details. Setting determination to obtain regular quality of welded joint is then chosen, and simple pre-experiment has conducted to find it. The result, a safe setting for friction pressure is set to 50 bar and friction time at 5 seconds to ensure that both materials is perfectly welded with regular form of welding flash. Table 2 presents factors and levels determination for the experiment.

Table 2. Factors and levels determination

Factors	Settings during experiment
Friction pressure (bar)	Gradual change at friction time 5 seconds
Friction time (seconds)	Gradual change at friction pressure 50 bar
Forging pressure (bar)	fixed at 100
Forging time (seconds)	fixed at 3
Rotation speed (RPM)	fixed at 910
Experiment response (MPa)	Joint tensile strength

Main-experiment. Instead of applying standard design of experiment (DoE) technique, this research choose to conduct the experiment by using one-factor-at-a-time (OFAT) strategy [11]. The OFAT strategy in experiment may raise disadvantage, *i.e.,* no interaction between factors can be investigated within. Yet, in certain cases this strategy still play roles on industries for studying process or machine parameters [12, 13]. Therefore, the selected OFAT strategy in this research was expected to support the exploration of both factors settings as bases for further investigation including interaction and optimization.



(a) (b)

Fig. 3: Samples of friction welded materials, increasing parameter from left to right, (a) increasing friction time at 50 bar friction pressure, (b) increasing friction pressure at 5 seconds friction time

Based on settings in **Kesalahan! Sumber referensi tidak ditemukan.**, the experiment results in good joint of both materials. Fig. 3 shows welded material samples. Visually these specimens have good welding flash. More flash was formed at the AISI 1045, showing that it was more ductile than the AISI 304.

It was observed that in some cases RFW produced higher strength joint than the base metal. In this situation, ordinary tensile test cannot provide the real tensile strength of the welding joint. Alternatively, cross weld tensile test using notched specimen might be employed. However, preliminary experiment in the present study proved that during tensile test fracture took place at the joint. This is commonly found in RFW joint for dissimilar materials, where fracture tends to occur at the lower-strength material or at the joint. Thus, in this work, tensile test was performed according to standard of testing material, *i.e.,* ASTM E8 as shown earlier in Fig. 2. The broken samples that have been tensile tested can be seen in Fig. 4. The figure clearly indicates fracture at the joint of welded specimen.

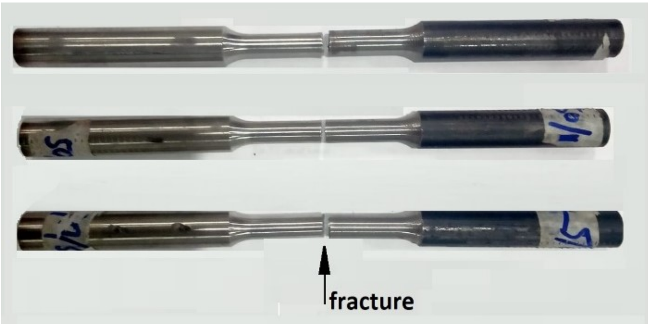


Fig. 4: Specimen is broken at the joint

Result and discussion

Tensile strength of the joint. The materials were successfully joined using RFW. Fig.3 presents the welded sample with combinations of low to higher friction parameters while maintaining other parameters (rotation speed, forging pressure, and forging time) constant. Perfect joint was produced at the friction pressure application as short as 3 seconds at 50 bar. Same condition was also yielded when the friction time was gradually increased while maintaining other parameters constant. Increasing friction pressure and friction time increasing heat the interface of the welded joint. The joint produced by lowest heating parameters is at the leftmost specimen in Fig. 3. Thus, the specimen at the leftmost underwent the RFW process with lowest heat. Conversely, the specimen at the rightmost received highest heat during the welding. The higher heat softens more the material. This leads the specimen to deform more easily. Therefore, more flash produced at the joint. Fig. 3 reveals that increasing friction pressure or friction time enhances the flash formation at the joint.

During the tensile test, fracture occurred at the joint. Maximum tensile test was observed at 30 bar friction pressure (friction time is constant at 5 seconds). At this combination, the tensile strength is 596.41 MPa. Varying the friction time (at constant pressure of 50 bar), the highest tensile strength, *i.e.,* 593.81 MPa, was achieved at 5 seconds. The maximum tensile strength of the joint is much less than the strength of AISI 1045 and AISI 304 steels (*i.e.,* 717 MPa and 730 MPa respectively). Hence, maximum efficiency of the welding is 82.9% (compared to AISI 1045) and 81.7% (compared to AISI 304). This efficiency is lower than the joint of friction welded AISI 1045 and AISI 316 [4]. Friction welding of those material may produce 90% welding efficiency. Neither reduction of area nor elongation were exhibited in the fractured specimen. This implies brittle fracture of the joint. Several phenomena may be responsible for this brittleness. Martensite might be formed near the joint interface. This was detected at the 4340 steels when it was friction welded with AISI 304 [5]. Carbide formation due to elemental diffusion might also take place [4]. This may contribute to the brittleness and lead to lower strength. Further study on the microstructure and elemental diffusion at the joint is required to figure out the phenomenon.

More flash at the joint can be an indication of perfect heating and upsetting as well as perfect joining. However, the amount of flash at the joint does not linearly corelate with the tensile strength. Polynomial model of tensile strength as given in Fig. 4 illustrates that increasing pressure, or time brings to higher strength. Maximum tensile strength was achieved at between 30 to 40 bar friction pressure. However, increasing the pressure further decreased the tensile strength. It came to the lowest value at 90 bar which is the maximum friction pressure in the experiments. When the friction was varied, the maximum tensile strength was obtained at the friction time as short as 5 seconds.

Clearly, the range of ideal friction pressure setting is narrow. Sufficient heat is required for the material to deform during the welding process. This will yield the joint. Higher heat also pushes brittle phase out of the joint interface and creates better strength. However, excessive heat can also bring to excessive deformation which may cause lower strength [7]. Refer to flash formation at the joint (Fig. 3), more flash indicates high heat produced by the parameters at the joint. The extreme flash possibly transfer heat to ambient. It may happen as this area was at expose to ambient. Therefore, the heat may move from the material to surroundings. This will reduce the ability of the material to deform which is required to form good joint.

Polynomial model of tensile strength. As all the experiment runs have conducted, the measured tensile strength data have been recorded and presented in Table 1. Since there is only a single replication in each treatment and no variation within, then a standard ANOVA analysis cannot be applied. Refer to the purpose of this research, *i.e.,* capturing the fluctuation of tensile strength as gradual change of each factor, the statistical analysis leads to fit the data trend with polynomial model. Evaluation of model refer to standard criteria as in regression model, such as coefficient of determination (R^2) and statistical assumption fulfilment.

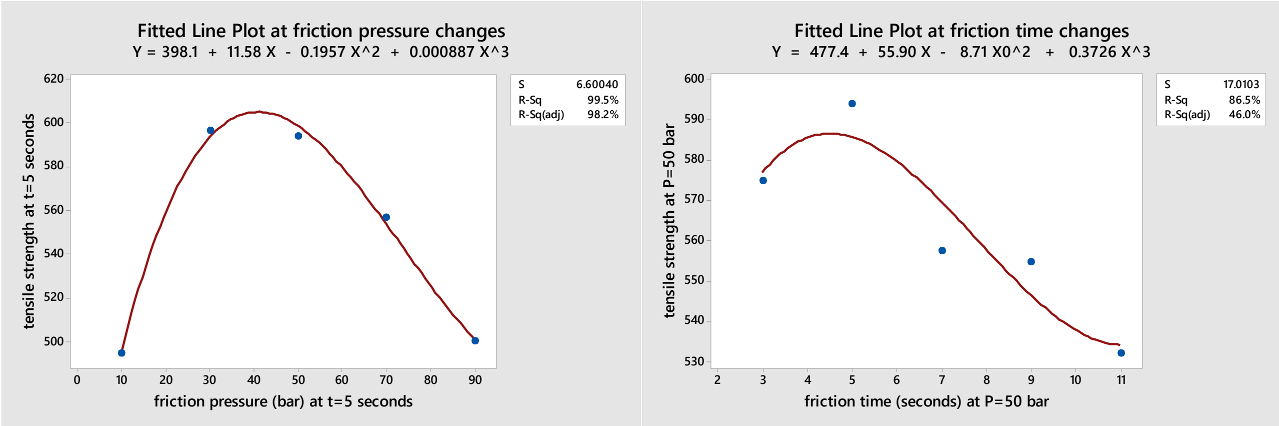
Considering the R^2 criteria, the best polynomial model for both pressure and time changes is cubic regression (see Fig. 1), details of model is written in Eq. 1 and Eq. 2.

$$Y = 398.1 + 11.58\,X - 0.1957\,X^2 + 0.000887\,X^3, \quad R^2 = 99.5\%. \qquad (1)$$
$$Y = 477.4 + 55.90\,X - 8.71\,X^2 + 0.3726\,X^3, \quad R^2 = 86.5\%. \qquad (2)$$

Table 1. Measured tensile strength

Experiment run	Friction pressure (bar)	Tensile strength (MPa)	Fixed setting
1	10	494.41	Friction time fixed at t = 5 seconds
2	30	596.41	
3	50	593.81	
4	70	556.78	
5	90	500.25	
Experiment run	**Friction time (seconds)**	**Tensile strength (MPa)**	**Fixed setting**
6	3	574.71	Friction pressure fixed at P = 50 bar
7	5	593.81	
8	7	557.43	
9	9	554.61	
10	11	532.09	

With a third level order of polynomial model, the curve starts to move upward and reaches a maximum value at a certain point. Afterward, it goes downward as friction pressure or time increases. This trend for both factors show that, increasing the friction pressure of friction time does not always give stronger joint. At certain value, there is a potential optimum point that can be a reference for further experiment and analysis, such as response surface methodology or Taguchi orthogonal array.



(a) (b)

Fig. 1. Polynomial model fit for pressure changes (a), and time changes (b).

The OFAT strategy in this result did not provide clear analysis if any interaction occurred between the factors. The results showed only individual effect of each factor and gave the fitted polynomial model. Thus, the conclusion also excluded the interaction effect. For further exploration of the factors' interaction, one should consider applying factorial design of experiment.

Conclusion

Experiments in RFW of AISI 1045 and AISI 304 steels were conducted in this present wok. The objective was to investigate the influence of friction time and friction pressure on the joint strength. The materials were successfully joined. Welding efficiency of the joint was 81.7% compared to the AISI 304 base metal and 83.1% compared to the AISI 1045.

Polynomial model of the parameter with tensile strength was also developed. The graphic fluctuation suggested that friction pressure and friction time influenced the tensile strength. A best fitted cubic mathematical model showed that at low setting, tensile strength went up when the friction time or friction pressure was raised. It reached a maximum point before decreasing as the setting continuously increased. It indicated a potential optimal point to obtain the best tensile strength. When this point was achieved, increasing setting value of each factor did not result in higher tensile strength anymore. This optimum point was marked at 40 bar friction pressure when the friction time was maintained constant. When the friction pressure was fixed, the optimum friction time was 5 seconds. There were potential interactions between both factors, nevertheless this research only considered to explore the individual factor. Further research should be taken to accommodate interaction.

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