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Optimization of Friction Welding Parameters for Joining Medium Carbon Steels using Response Surface Methodology

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***Abstract*— Friction welding is one of the most economical, highly effective and practicable methods in joining similar and dissimilar metals. As a mass production process for joining materials, friction welding finds widespread industrial use. Friction welding process allows welding of several materials that are extremely difficult to fusion weld. Friction welding process parameters play a significant role in making good quality joints. To produce a good quality joint it is important to set up proper welding process parameters. This can be done by employing optimization techniques. In this study, high-quality welds are produced in the medium carbon steel by continuous drive friction welding successfully. Design of experiment was done using central composite design of response surface methodology (RSM) for optimizing the process parameters. The joints are welded with various parameter combinations incorporating ANOVA method. Tensile strength of friction welded 12mm diameter medium carbon steel (AISI 1035) joints were investigated considering various process parameters: friction force (F), upset force (U) and rotational speed (N). Direct and interaction effects of process parameters on responses were studied by plotting graphs. The empirical relationships are established to predict the ultimate tensile strength of the welded joints. The consistency of the model has been checked. . The proposed method combines the response surface methodology (RSM) with an intelligent optimization algorithm, i.e. genetic algorithm (GA) for maximizing the tensile strength**

***Keywords*— response surface methodology;analysis of variance; friction welding parameter; optimization**

I. INTRODUCTION

Welding, as a technological process, is widely practiced in modern engineering. Welding and joining technology is fundamental to Engineering and Manufacturing. Without the ability to make strong and durable connections between materials it would not be possible to produce the many different items upon which we all rely in our everyday lives, from the very large (buildings, pipelines, trains and bridges) to the very small (medical implants and electronic devices). In conventional welding process, a filler material is added to the outside edges of a joint with the help of an outside heat source such as a torch flame. The welding processes currently used in fabrication and construction industry basically involve the deposition of weld metal by arc processes which may be manual, semi or fully mechanized. All of these processes involve the preparation of the joint edges and multi pass techniques in order to achieve full penetration for the thicker sections. The main limitations of above mentioned techniques are associated-with , use of expensive filler materials, possible use of pre-heat, low joining rates, requirement for skilled labour, use of expensive filler materials restrictions on welding position and there are many other problems of metallurgical nature concerned with weld defects and joint properties, particularly toughness. However, the availability of a mechanized process capable of a high joining rate would be a considerable breakthrough. It is considered that both friction and electron beam welding offer great potential in this area.

Friction Welding (FRW) is a solid state welding process which produces welds due to the compressive force contact of workpieces which are either rotating or moving relative to one another. Heat is produced due to the friction which displaces material plastically from the faying surfaces [1,2]. Friction welding can achieve high-production rates and therefore is economical in operation. It have widespread industrial uses and helps to weld materials which are extremely difficult to join by fusion welding. Various ferrous and non-ferrous alloys, which have circular or non-circular cross-sections and, having different thermal and mechanical properties, can easily be joined by the friction welding method. When joining dissimilar metals such as Aluminium, Copper and Steel, friction welding is of great importance in applications. The main process parameters of friction welding are rotation speed, friction pressure, friction time, upset pressure and upset time and these process parameters have significant role in making good quality joints [3].

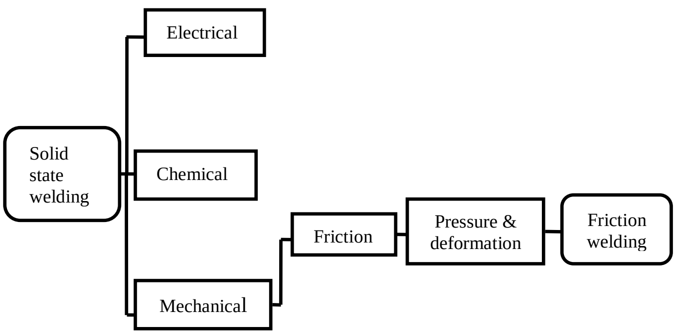

Fig. 1. Classification of solid state welding.

So to get a good quality welding joint, it is significant to select proper combinations of process parameters. To produce the desired response, the first step is to identify the suitable combinations of process variables and it requires many experiments, making this process time consuming and costly [4]. So to rectify this situation, mathematical models can be built which can adequately predict the relation between input process parameters and the responses. Response surface methodology (RSM) [5] is widely used for this purpose.

The medium carbon steel of grade AISI 1035 has plenty of industrial applications such as in automobile industries, machine parts, shipbuilding because of its high mechanical strength.

From the literature survey, Murti and Sundaresan [6] have studied friction welding of dissimilar materials using statistical approach based on factorial design of experiment through friction welding parameter optimization. Sahin and Akata [7] have done an experimental study on application of friction welding for parts with different diameter and width by using tensile test. Sathiya et al. [8] have done the optimization of friction welding parameters using evolutionary computational techniques. The methods suggested in this study were used to determine the welding process parameters by which the desired tensile strength and minimized metal loss were obtained in friction welding. This study describes how to obtain near optimal welding conditions over a wide search space by conducting relatively a smaller number of experiments. The optimized values obtained through these evolutionary computational techniques were compared with experimental results. The strength and micro structural aspects of the processed joints were also analyzed to validate the optimization. Paventhan et al [9] have done the optimization of friction welding process parameters for joining carbon steel and stainless steel. They developed an empirical relationship to predict the tensile strength of friction welded AISI 1040 grade medium carbon steel and AISI 304 austenitic stainless steel, incorporating the process parameters such as friction pressure, forging pressure, friction time and forging time, which have great influence on strength of the joints. Response surface methodology was applied to optimize the friction welding process parameters to attain maximum tensile strength of the joint. The maximum tensile strength of 543 MPa could be obtained for the joints fabricated under the welding conditions of friction pressure of 90 MPa, forging pressure of 90 MPa, friction time of 6 s and forging time of 6s.

II. EXPERIMENTAL WORKS

A. *Material Selection)*

. Knowledge on material properties and applicability of metallic materials and material combinations for friction welding is not completely clear. Experimental studies and practical applications have been given to address this problem. Preliminary trials have been carried out in order to determine optimum parameters of welding, the applicability of welding process for every new material or material combinations. The results of these studies are not concrete since they are experimental. They can be modified or redefines as new facts come out. The main two parameters needed for the test of suitability of a material to welding are the strength of a material and its deformation capacity under heat. The strength of material has to be high enough to resist axial pressure and torque, which may occur due to excessive deformation. Moreover, the material to be joined needs to exhibit enough heat treatment deformation behavior for the quality of joining process. In this study medium carbon steel (AISI 1035 grade) is used as the base material. The chemical composition of the base material AISI 1035 is given in Table 1. The samples have 12 mm diameter extruded rod and 100 mm length.

TABLE I. CHEMICAL COMPOSITION OF AISI 1030

Elements	C	P	Si	S	Mn	Fe
%	0.33	0.04	0.20	0.05	0.64	Balance

B. *Experimental design based on response surface methodology*

Based on the literature survey it was observed that the process parameters have a significant effect on the tensile strength. Process parameters like friction force, friction time, rotational speed, upset pressure, upset time, burn of length. Among the above parameters, the friction force, upset force, and rotational speed are more important because these parameters affect weld joint quality. These process parameters are set based on the survey in the field. In the present study, the process parameters selected are friction force / friction time (F), upset force / upsetting time (U), rotational speed (N). Other parameters are kept constant. The working ranges of all selected parameters were fixed by conducting trial runs. This was carried out by varying one of the parameters while keeping the rest of them at constant values. The working range of each process parameter was decided upon by inspecting the weld for a smooth appearance without any visible defects. The upper and lower limits with different levels of the identified process parameters are given in Table 2.

TABLE II. PROCESS VARIABLES AND ITS BOUNDS

Parameter	Unit	Level		
		(-1)	(0)	(+1)
Friction pressure/friction time (F)	MPa/s	15	30	45
Upset pressure/upset time (U)	MPa/s	15	30	45
Rotational speed (N)	rps	18	23	28

The Design of Experiments (DOE) was done by Response surface methodology (RSM) using Design Expert version 6.0.8 statistical software. The design matrix chosen to conduct the experiment was a Central Composite Design (CCD) having 20 experiments. Thus the 20 experimental runs allowed the estimation of linear, quadratic and two-way interactive effects of the process parameters on tensile strength.

The friction welding machine "FWG 20/300-S" is a machine capable of operating with high precision and excellent repeatability of all weld parameters. The spindle is driven by an AC spindle motor. Friction and upset forces are read by a load cell and precisely controlled by a hydraulic servo valve. The machine is controlled by an individual computer and the data of every weld is recorded. There is provision for retrieval of weld data.

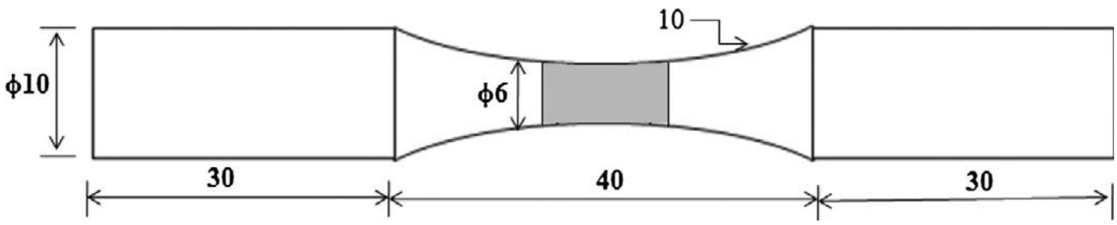

Fig. 2. Dimensions of tensile test specimen.

The machine has a stroke of 300 mm and a maximum upset force of 200 kN can be applied. The spindle motor is of 20 HP, 3 phase AC and operating speed can be varied from 1 to 2500 RPM. As per the DOE, 20 friction welded samples were made. The welding was carried out at ETA Technology pvt ltd, Bangalore, Karnataka using a continuous drive friction welding machine. The experiments were carried on AISI 1035 grade carbon steel rods of size 12 mm in diameter and 100 mm length. The welded joints are machined to the dimensions as shown in Fig. 1. The ASTM guidelines are followed in preparing the tensile test specimens. Tensile test is carried out on a 100 kN electromechanical controlled universal testing machine (FIE-Blue Star, India; capacity: 0–100 kN, model: Instron-UNITEK-94100). The specimen is loaded at the rate of 1.5 kN per minutes according to the ASTM specifications

TABLE III. DESIGN MATRIX AND CORREESPONDING TENSILE STRENGTH

Exp No.	Coded units			Uncoded units			Tensile Strength (MPa)
	F	*U*	*N*	*F(MPa/s)*	*U(MPa/s)*	*N(rps)*	
1	-1	-1	-1	15	15	18	410
2	1	-1	-1	45	15	18	434
3	-1	1	-1	15	45	18	421
4	1	1	-1	45	45	18	429
5	-1	-1	1	15	15	28	468
6	1	-1	1	45	15	28	448
7	-1	1	1	15	45	28	466
8	1	1	1	45	45	28	428
9	-1	0	0	15	30	23	507
10	1	0	0	45	30	23	500
11	0	-1	0	30	15	23	510
12	0	1	0	30	45	23	510
13	0	0	-1	30	30	18	501
14	0	0	1	30	30	28	534
15	0	0	0	30	30	23	547
16	0	0	0	30	30	23	546
17	0	0	0	30	30	23	548
18	0	0	0	30	30	23	545
19	0	0	0	30	30	23	548
20	0	0	0	30	30	23	545

III. RESULTS AND DISCUSSIONS

The tensile strength values are given with corresponding friction welding process parameters in the Table III. The response function representing tensile strength can be expressed as:

Y = f (F, U, N)

Where Y is the response or yield, F is the friction pressure/time, U is the Upset pressure/time and N is the rotation speed. The significance of each coefficient is determined by 'F' and 'p' values, which are listed in Table V. The value of the coefficient is calculated using the Design Expert Software.

The mathematical model to establish the relationships between input and output parameters were developed using Design expert software at a confidence level of 95%, based on the experimental data collected as per the Central Composite Design based on Response Surface Methodology (RSM). Tensile strength is expressed in the form as a non-linear function of process parameters. The final empirical relationship was constructed using only these coefficients, and the final empirical relationship obtained in uncoded values for tensile strength 'TS'. The regression equations in terms of actual factors thus obtained tensile strength is as follows

Tesile Strength TS = —596.58000 + (15.26333*F) + (11.26667*U) + (62.24*N) — (0.19111* F^2) — (0.16222*U^2) — (1.16*N^2) — (0.018889*F*U) — (0.15* F*N) — (0.046667*B*N).

S1 = 0.0000566622, R-Sq = 99.95% R-Sq(pred) = 99.97% R-Sq(adj) = 99.91%, Where, (S1= Root mean squared deviation, R-Sq = Coefficient of correlation).

The multiple linear regression coefficients for the second-order response surface model are given in Table IV.

TABLE IV. ESTIMATED REGRESSION COEFFICIENTS

Factor	Estimated regression coefficient (Tensile strength)
Intercept	-596.58000
F-friction force/friction time	+15.26333
U-upset force/upsetting time	+11.26667
N-rotational speed	+62.24000
FU	-0.018889
FN	-0.15000
UN	-0.046667
F^2	-0.19111
U^2	-0.16222
N^2	-1.16000

TABLE V. ANOVA TEST RESULTS FOR THE RESPONSE TENSILE STRENGTH

Source	Sum of squares	DF	Mean square	*F* value	*p*-value (prob > *F*	
Model	*46970.85*	*9*	*5218.98*	*2279.03*	< 0.0001	significant
F	*108.90*	*1*	*108.90*	*47.55*	*< 0.0001*	
U	*25.60*	*1*	*25.60*	*11.18*	*0.0074*	
N	*2220.10*	*1*	*2220.10*	*969.48*	*< 0.0001*	
F^2	*5084.75*	*1*	*5084.75*	*2220.41*	*< 0.0001*	
U^2	*3663.69*	*1*	*3663.69*	*1599.86*	*< 0.0001*	
N^2	*2312.75*	*1*	*2312.75*	*1009.93*	*< 0.0001*	
FU	*144.50*	*1*	*144.50*	*63.10*	*< 0.0001*	
FN	*1012.50*	*1*	*1012.50*	*442.14*	*< 0.0001*	
UN	*98.00*	*1*	*98.00*	*42.79*	*< 0.0001*	
Residual	*22.90*	*10*	*2.29*			
Lack of fit	*13.40*	*5*	*2.68*	*1.41*	0.3575	*Not significant*
Pure error	*9.50*	*5*	*1.90*			
Cor. total	*46993.75*	*19*				

Std. dev. = 1.51, mean = 492.25, C.V. = 0.31%, PRESS = 124.04, R2 = 0.9995, adj. R2 = 0.9991, pred. R2 = 0.9974, Adeq. Precision = 128.499

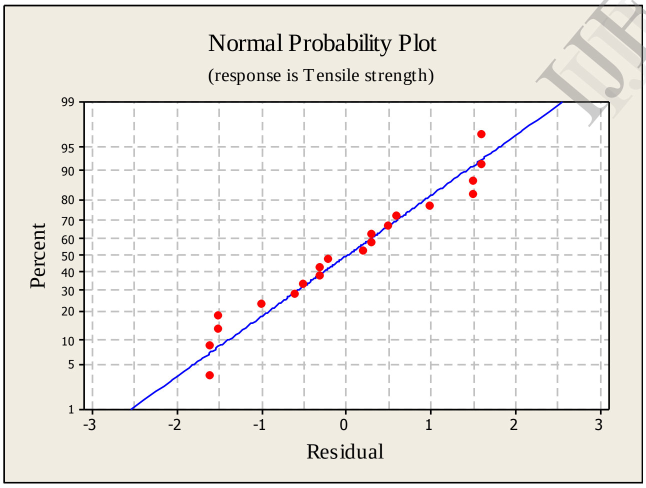

Fig. 3. Normal probability plot of tensile strength.

The normal probability plot of the residuals for tensile strength is shown in Fig. 3. It reveals that the residuals are falling on the straight line, which means the errors are distributed normally [10].

Analysis of variance (ANOVA) technique was used to check the adequacy of the developed empirical relationship. In this investigation, the desired level of confidence was considered to be 95%. The relationship may be considered to be adequate, which provides that 1) the calculated F value of the model developed should not exceed the standard tabulated F value and 2) the calculated R value of the developed relationship should exceed the standard tabulated R value for a desired level of confidence. It is found that the above model is adequate. Each predicted value matches well with its experimental value, as shown in Fig.4. For 95% confidence, the p-value must be less than 0.05. The results of basic ANOVA are presented in Table V. From the results obtained it is clear that the p-value for the model lie below 0.05. Thus the model can be considered adequate within the confidence limit.

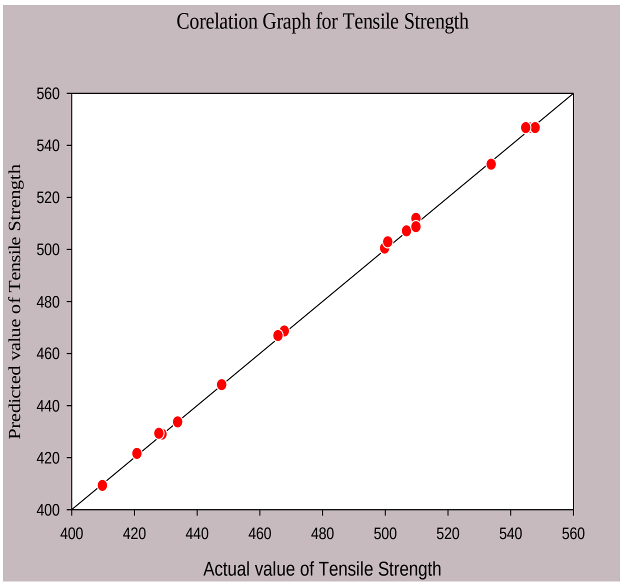

Fig. 4. Correlation graph for tensile strength.

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A. Individual Effects Of Process Parameters On Responses

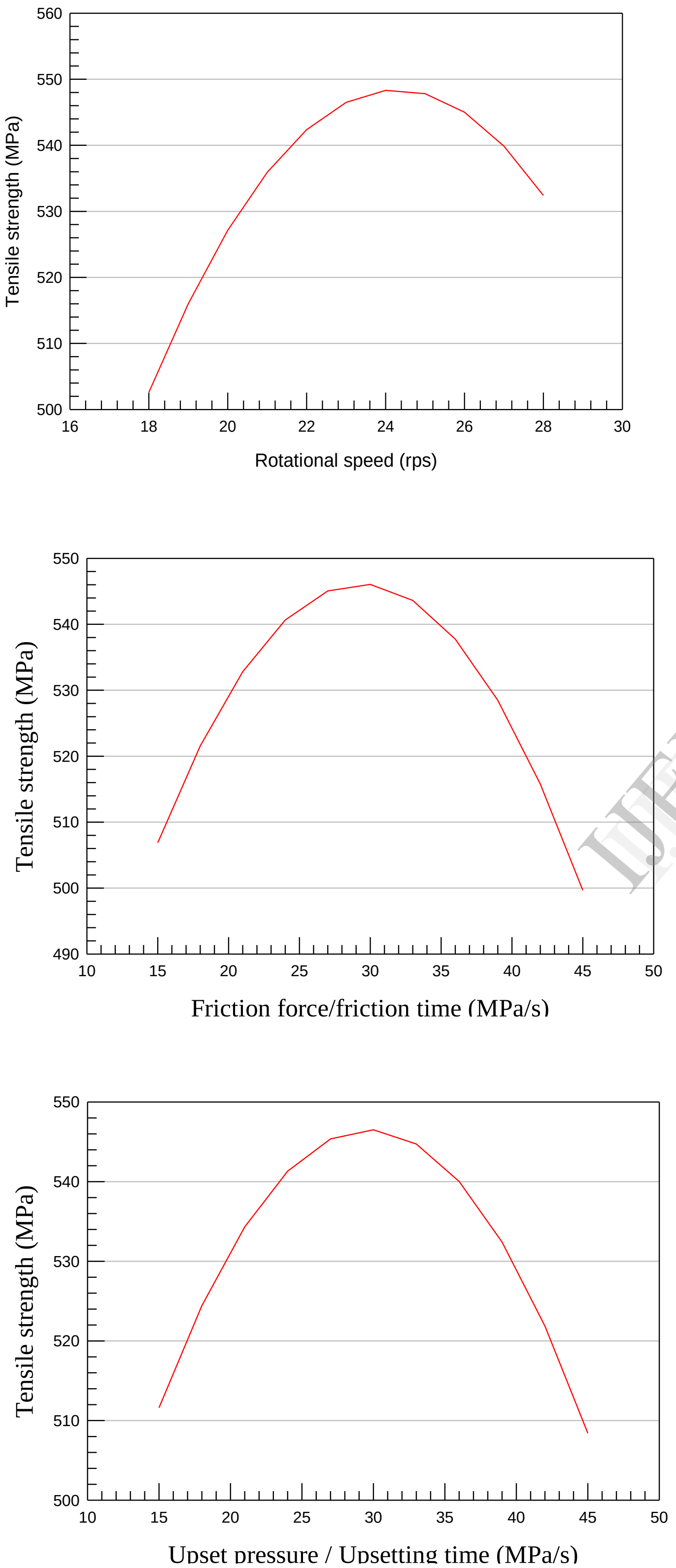

Fig. 5. Individual effects of process parameters on response

Based on the regression equations, the variation of the responses with respect to each of the three process parameters friction force / friction time, upset force / upsetting time and rotational speed were plotted by keeping two parameters constant at their middle level and varying the third within the upper and lower bounds. The individual effects of each parameter on tensile strength, response, can be representing in graph as shown in Figure 5.

B. Interaction Effects Of Process Parameters On Responses

Interactive effects of process parameters on the response are shown using contour plots. Contour plots have generated using Minitab 16 software for all pairs of factors. Contour plots for Impact Strength are shown in the figure 6.

Response surface methodology (RSM) is used to optimize the friction welding parameters in this study. RSM is a collection of mathematical and statistical techniques that are helpful for designing a set of experiments, analyzing the optimum combination of input process parameters, developing a mathematical model, and expressing the values graphically. Surface plots and contour plots are the indications of possible independence of factors .To obtain the nature of influence and optimized condition of the process on tensile strength, surface plots and contour plots have been developed for the empirical relation by considering one process parameters in the middle level and two process parameters in the X and Y axes. These response contours can assist in the prediction of the response for any zone in the experimental field. The apex of the response plot shows the maximum achievable tensile strength. Figs. 6 show that, the tensile strength increases with increasing the friction pressure/time and rotational speed and then decreases. But the tensile strength increases with decreasing the forging pressure/time.

A contour plot is produced to display the region of the optimal factor settings visually. For second- order responses, such a plot can be more complex compared to the simple series of parallel lines that can take place with first-order models. Once the stationary point originates, it is generally necessary to characterize the response surface in the immediate vicinity of the point. Characterization involves identifying whether the stationary point is a saddle point or minimum response or maximum response.

From these values, it is inferred that the predicted and experimental optimized strength values are in good agreement and the variations is found to be less than ±10%. Contributions made by the process parameters of strength of the joint can be ranked from their respective ‘F’ ratio value which is presented in Table V. The higher F ratio value implies that the respective term is more significant and vice versa. From the F ratio values, it can be concluded that the rotational speed is found to have greater influence on tensile strength of the joints followed by forging pressure/time and friction pressure/time within the range considered in this investigation.

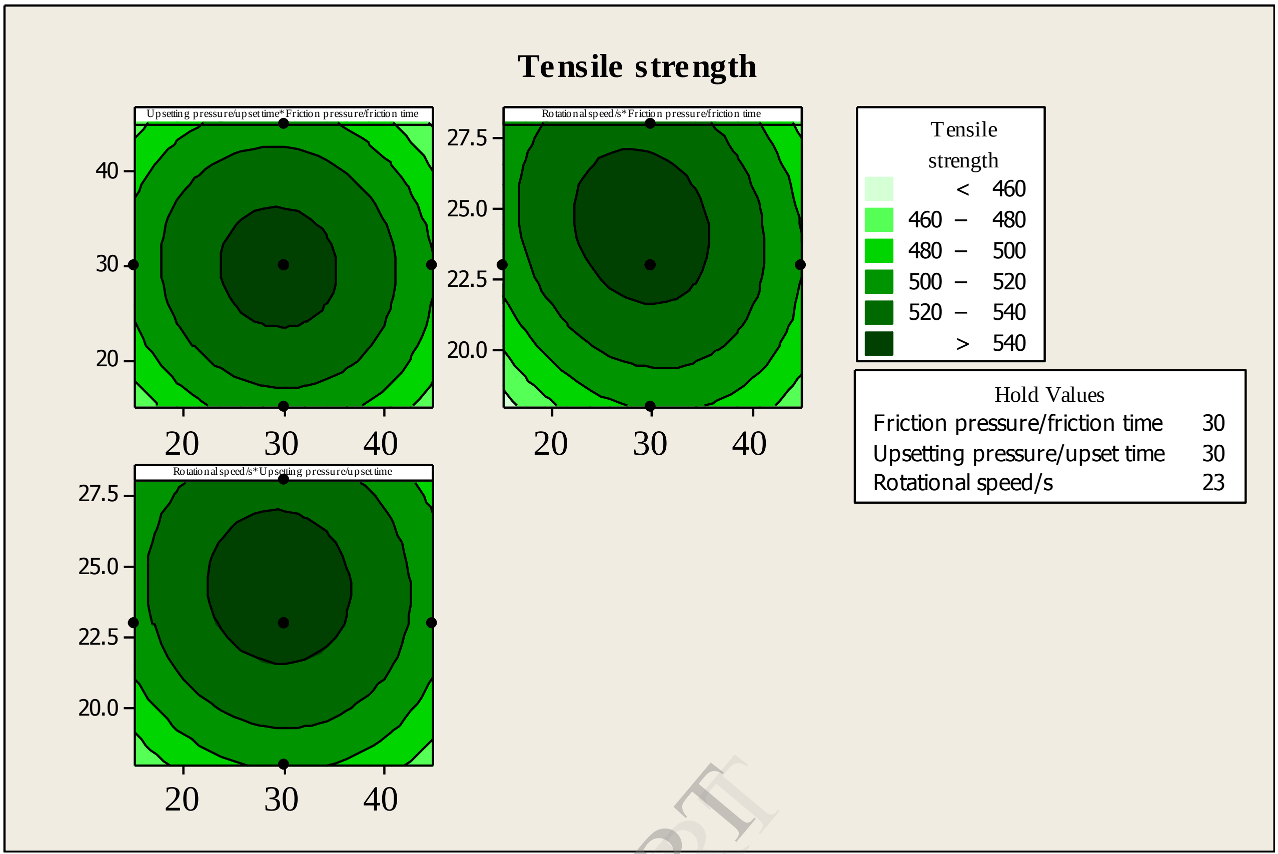

Fig. 6. Interaction effects of process parameters on responses

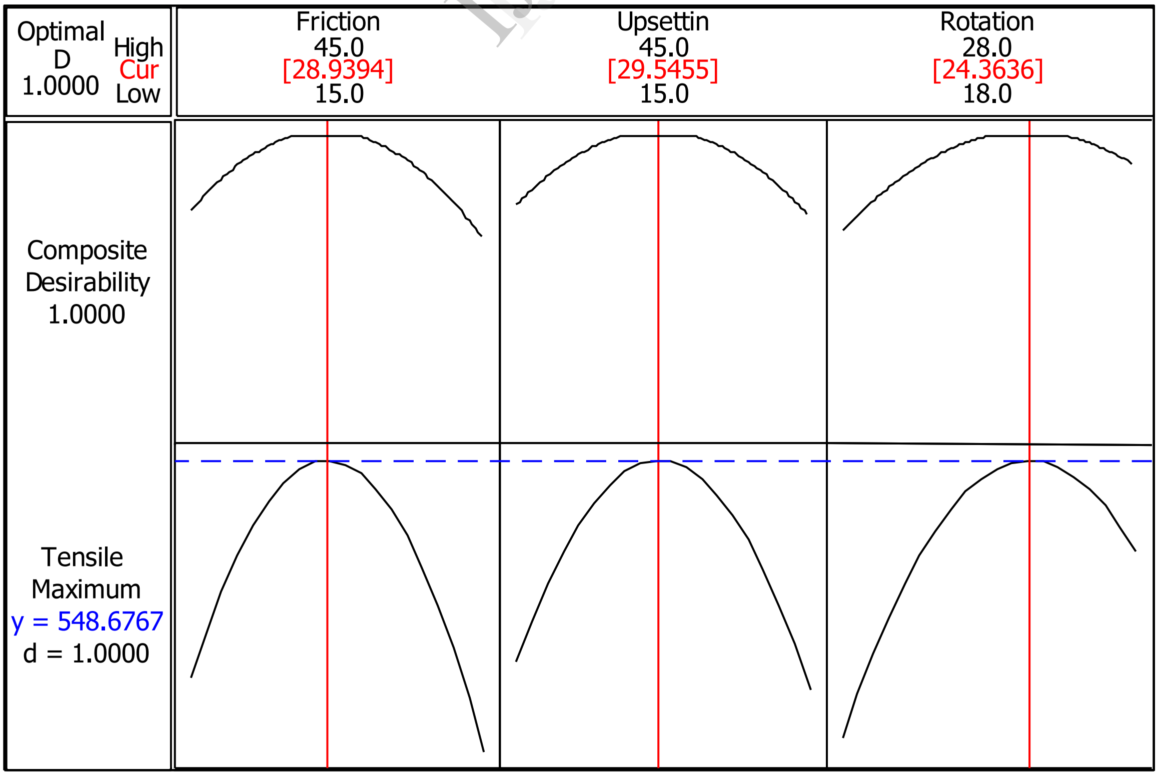

Fig. 7. Optimization plot for maximum tensile Strength

A predicted maximum tensile strength of the friction welded specimen is 548.6767 MPa could be attained under the welding conditions of 28.9394 MPa/s (86.8182 MPa of friction pressure and 3 s of friction time) of friction pressure/time, 29.5455 MPa/s (86.8638 MPa of forging pressure and 2.94 s of forging time) of forging presses/time and 24.3636 rps of rotational speed. The experimentally determined tensile strength was found to be 548 MPa and could be attained under the welding conditions of 30 MPa/s (90 Mpa of friction pressure and 3 s of friction time) of friction pressure/time, 30 MPa/s (90 MPa of forging pressure and 3 s of forging time) of forging pressure/time and 23 rps of rotational speed which shows the consistency of the model.

TABLE VI. RESPONSE OF SURFACE OPTIMIZATION

	F (MPa/s)	U (MPa/s)	N (rps)	Tensile Strength (MPa)
Optimized values	28.9394	29.5455	24.3636	548.6767

C. Optimization Of Friction Welding Parameters Using Genetic Algorithm

Based on the mathematical models developed, the tensile strength was optimized using the proposed evolutionary algorithm. The optimization process was performed using Matlab R2010a software.

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population ‘‘evolves’’ toward an optimal solution. Genetic algorithm can be applied to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear.

The genetic algorithm uses three main types of rules at each step to create the next generation from the current population. Selection rules select the individuals called parents which contribute to the population at the next generation. Crossover rules combine two parents to form children for the next generation. Mutation rules apply random changes to individual parents to form children [11].

Global optimization toolbox in MATLAB (R2010a) was used for generating the optimum values of three friction welding parameters. A MATLAB function was written using the developed RSM models. Then this function was called as the input for creating a fitness function for the optimization problem. The impact strength to be maximized was negated in the fitness function since genetic algorithm minimizes all the objectives. Experimental ranges were placed as bounds on the three input variables which are shown below:

- Bounds on friction force

  $15 \leq F \leq 45$

- Bounds on upset force

  $15 \leq U \leq 45$

- Bounds on burn off length

  $18 \leq N \leq 28$

The weighted average change in the fitness function value over 50 generations was used as the criteria for stopping the algorithm. The optimized parameter values have achieved after 50 iterations is shown in Fig. 8.

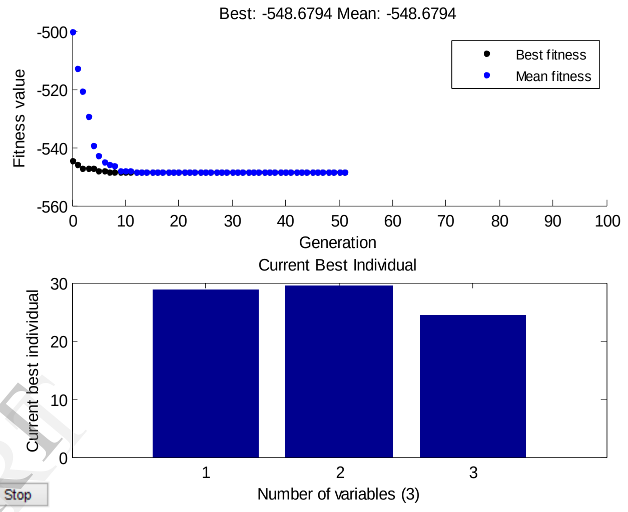

Fig. 8. Genetic algorithm output

TABLE VII. COMPARSON BETWEEN RSM AND GA OPTIMIZATION

No.	Methods	Tensile Strength(MPa)	*F(MPa/s)*	*U(MPa/s)*	*N(rps)*
1	RSM	548.6767	28.9394	29.5455	24.3636
2	GA	548.6794	28.913	29.539	24.364

IV. CONCLUSION

In this study, Friction welding process parameters were optimized using response surface methodology and evolutionary algorithm such as Genetic Algorithm. The friction welding was carried out as per the design of experiments by central composite design. Tension test was carried out for friction welded samples and the results are recorded. Based on the experimental results, regression analysis was conducted with the help of Minitab-16 and Design-Expert softwares, to determine input–output relationships of the process. Based on the mathematical model developed, the responses were predicted and correlation graphs were plotted. The regression equations were then plotted and the effects of each process parameter on tensile strength were analyzed. The process parameters were then optimized using RSM to yield maximum tensile strength. The same problem was then optimized using GA, and the results were compared with the help of Matlab software. Based on the experimentation and optimization the following conclusions are drawn:

1) The empirical relationships are developed to predict the tensile strength of the friction welded AISI 1035 steel rods incorporating process parameters at 95% confidence level.
2) The optimum condition for tensile strength 548.6767 MPa could be attained in friction welded AISI 1035 grade medium carbon steel rods under the welding conditions of 28.9394 MPa/s of friction pressure/time, 29.5455 MPa/s of upset pressure/time and 24.3636 rps of rotational speed.
3) The process parameters have a significant effect on tensile strength and rotational speed was found to have greater influence on tensile strength of the joints followed by upset pressure and friction pressure.
4) The fusion zone of rotating side has more width than the stationary side. This will lead the hardness to be higher than the stationary side of the welded specimen.

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