Meta-heuristic optimization of copper friction stir weldments

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Abstract: *This work focused on the optimization of process parameters, which may result in increasing mechanical properties of copper weldments. The different tool pin profiles such as plain taper cylindrical, taper cylindrical with threaded, triangular, square, pentagonal and hexagonal having constant shoulder diameters were used to fabricate the weldments. The experiments were conducted at different levels of tool rotational speed and weld speeds using six different tool pin profiles. The experimental results revealed that the defect free weldments could be obtained by using different tool pin profiles. From the investigation, it was found the weldments made by using a square (SQ) tool pin profile resulted in better mechanical properties compared to other tool pin profiles. Objective functions are developed for the mechanical properties in terms of input parameters. The input parameters of an SQ tool pin profile were optimized using a metaheuristic optimization based algorithm named teaching learning based optimization (TLBO) technique to improve mechanical properties. The TLBO suggests a combination of 900 rpm of tool rotation speed and 40 mm/min weld speed for better properties.*

Key Words: *Friction stir weldments, mechanical properties, TLBO, Mathematical models, Multi-objective optimization*

1. INTRODUCTION

Current advances in the metal joining process produce better results and reduce costs related to policy, execution time and quality of existing methods. These conflicts were overcome by adopting friction stir welding (FSW) in metal joining. It is found at The Welding Institute (TWI) and is used effectively for joining metals, that are difficult to fusion welding [1-3]. Copper and its alloys are important engineering materials due to their smart mobility, corrosion resistance, electrical and thermal conductivity [12]. Welding of copper is sometimes difficult through standard fusion welding processes due to high fusion. FSW is one of the solid-state

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welding processes in which the unusable rotating welding tool pin plunges into the joint line between the two plates. FSW is environmentally friendly, less deformable, energy efficient, has a faster welding speed than older fusion welding methods and materials that are difficult to fusion welds [15]. Copper is used in container bins for nuclear waste, which is made by the FSW method [16]. The manufacture of support plates of copper alloys has been used for sputter devices [17]. The presence of tool pin profiles affects the flow of plasticized material and affects weld characteristics [18, 19]. The axial force on the work material and the flow of material near the tool are affected by the orientation of the thread on the pin surface [20]. Material flow behaviour is predetermined by the FSW tool pin profile, tool dimensions, and process parameters [21]. From the reported literature, it is observed that there is limited work on copper weldments on the mechanical properties of copper welds using different tool pin profiles. Therefore, the present study aims at the effect of different tool pin profiles on the mechanical properties of FS welds. In addition, process parameters such as tool rotational speed (TRS), weld speed (WS) and tool tilt angle (TA) play an energetic role in producing the quantities required for quality welds in solid-state welding. They also help to generate heat influencing the fine grains in the weld area [4, 5].

Currently, the researchers are focused on the optimization of process parameters to achieve better quality weldments [6-9]. In particular, parameters such as TRS and WS of the tool affect the mechanical properties, such as ultimate tensile strength, yield strength, and percentage of elongation in FSW welds. All evolutionary and herd intelligence-based optimization algorithms require common control parameters such as population size, number of generations, and high size. In addition to general control parameters, various algorithms require their own algorithm-specific parameters. For example, GA uses mutation probability and crossover probability and selection operators; PSO uses inertia weight and social and cognitive parameters; The ABC algorithm uses the number of bees (scout, gender, and job) and scope; And NSGA-II requires crossover probability, mutation probability, and distribution index. Proper tuning of these algorithm-specific parameters is a very important factor affecting the performance of the algorithm. Improper tuning of algorithm-specific parameters increases computational effort or achieves locally optimal solutions. In addition to adjusting algorithm-specific parameters, it is also necessary to tune common control parameters, which further increases effort. Therefore, there is a need to develop an algorithm that does not require algorithm-specific parameters, and TLBO is such an algorithm.

In TLBO, informative thinking is combined jointly to understand all strategies from teacher to learner, and from teacher or learner to implement the best strategy or achieve optimal results [10]. The present work focuses on the improvement of scientific models using TLBO to evaluate the mechanical properties of copper FS weldments. In order to use the effect of process parameters of the SQ tool pin profile on mechanical properties, parameters of different levels are presented in Table 2. The TLBO technique is used to optimize process parameters to achieve better mechanical properties. TLBO has been shown to outperform experimental studies.

2. METHODOLOGY

The present work is implemented in two stages, such as the experimentation and optimization of process parameters, as shown in Figure 1. In the first stage, various tool pins are used for weldments fabrication at different levels of TRS and WS. The weldments were evaluated. In the second stage, the optimization of process parameters is performed to improve mechanical properties using TLBO. In this step, an initial population using experimental data generates constraints according to tensile strength (TS), yield strength (YS), elongation percentage (EL), impact strength (IS), and hardness (H). The new process variables and their associated responses are obtained using the concept of diff_mean. Individual and overall constraints are estimated for all experiments and, consequently, experiments are sorted. The initial population and new population are combined to get the best solution based on the rank.

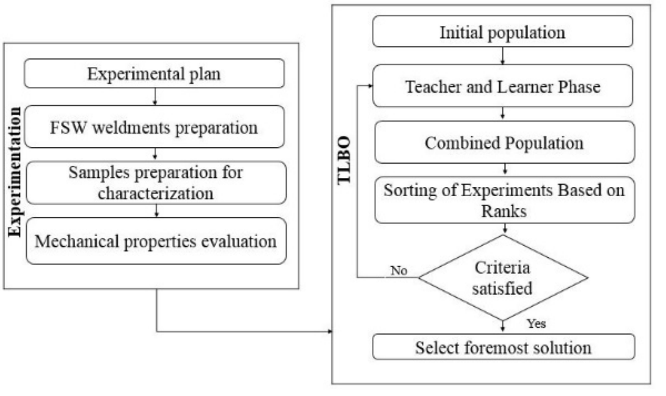

Figure 1. Flow chart of a process [11]

3. EXPERIMENTAL PROCEDURE

The 3 mm thick copper base metal (BM) sheet soaked the two plates and moved the milling tool assembly with a vertical milling machine. Each experiment started with a new FSW tool and the mechanical properties are presented in Table 1.

Table 1. Input parameters and experimental results

Tool pin profile	TRS (rpm)	WS (mm/min)	TS (Mpa)	YS (Mpa)	% EL	IS (J)	H(HV)
TC	900	40	168	109	13.5	13	85
TT	900	40	187	129	13.4	13	90
TR	900	40	208	151	14	14	95
SQ	900	40	212.07	167.06	14.98	14.34	98.94
PT	900	40	207	178	12	09	82
HX	900	40	183	141	3	08	80

The copper weldments were fabricated with different TRS and WS used with various tool pin profiles. From this, the improved properties were found to be TRS of 900 rpm and WS of 40 mm/min, respectively, and are listed in Table 1; [22]. From the surface morphology, it was observed that the amount of flash in the joints produced by the SQ tool pin profile was less than the pin profiles of the other joints. The welding parameters and mechanical properties of the welds performed by the SQ tool are presented in Table 2.

Table 2. Process parameters and mechanical properties of SQ tool pin weldments

Tool pin profile	TRS (rpm)	WS (mm/min)	TS (Mpa)	YS (Mpa)	% EL	IS (J)	H(HV)
Square tool	700	30	158.29	90.88	10.52	10.00	77.89
	700	40	171.71	108.78	12.47	12.02	86.84
	700	50	171.39	105.94	13.13	13.30	84.79
	900	30	205.39	156.22	15.09	13.11	91.49
	900	40	212.07	167.06	14.98	14.34	98.94
	900	50	205.01	157.16	13.59	14.82	95.39
	1100	30	194.17	158.84	8.62	7.82	78.45
	1100	40	194.11	162.62	6.46	8.26	84.40
	1100	50	180.31	145.66	3.01	7.94	79.35

For mechanical properties, friction stir weldments were sliced towards the transverse cross-section by wire cut EDM machine in the direction of welding according to ASTM-E8 and A370 standards. The schematic diagrams of the tensile and impact models are shown in Figure 2. Digital micro hardness tester (HVS-100B model) has been used to measure micro hardness in the weld area. The tensile test was conducted with the help of a computer controlled universal testing machine (Model: TUE-C-600) at a cross head speed of 0.5mm/min. The impact test was conducted at room temperature using pendulum type charpy impact testing machine.

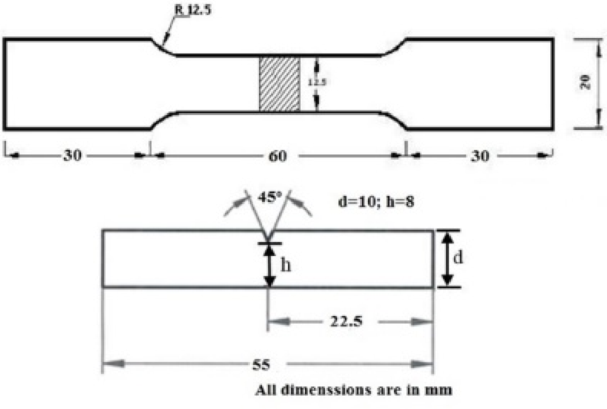

Figure 2. Schematic diagram of tensile and impact specimens

4. MULTI-RESPONSE OPTIMIZATION

The current study introduces a new incorporated technique for multi-response optimization of process parameters with TLBO.

This technique has been used to enhance mechanical properties. Process Parameters such as TRS, WS and their impact of H, IS, EL, YS, and TS were studied. The TRS and WS are considered to directly affect the production of frictional heat that causes the plastic flow of the material. When a combination of parameters produces too little or too much heat, the material flow is subsequently affected and it affects the weldment quality as well as mechanical properties.

Mathematical models are developed from the perspective of process parameters that are used to study the effect of process parameters at different levels on responses. These models can also be used to define the objective function for the optimization of process parameters [12-13].

The objective functions for H, IS, EL, YS, and TS for the SQ tool pin profiles were generated using MINITAB17 and are shown in (1) to (5). The present study focuses on the enhancement of H, IS, EL, YS, and TS.

Maximization:
Square tool pin profile

$$TS=-659.3+1.503*TRS+8.51*WS-0.000729*TRS*TRS-0.0687*WS*WS-0.00337*TRS*WS. \quad (1)$$

$$YS=-884+1.687*TRS+11.52*WS-0.000784*TRS*TRS-0.1037*WS*WS-0.00353*TRS*WS. \quad (2)$$

$$EL=-127.6+0.2745*TRS+1.366*WS-0.000138*TRS*TRS-0.00645*WS*WS-0.001028*TRS*WS. \quad (3)$$

$$IS=-86.0+0.1955*TRS+0.745*WS-0.000105*TRS*TRS-0.00377*WS*WS-0.000398*TRS*WS. \quad (4)$$

$$H=-288.1+0.6233*TRS+5.27*WS-0.000333*TRS*TRS-0.0550*WS*WS-0.000750*TRS*WS. \quad (5)$$

Constraints:

$$C_{TS}= TS\leq 260 \quad (6)$$

$$C_{YS}= YS\leq 231 \quad (7)$$

$$C_{EL} = EL\leq 31 \quad (8)$$

$$C_{IS}=IS \leq 18 \quad (9)$$

$$C_{H} = H \leq 110 \quad (10)$$

Parameter bounds:

$$TRS: 50\leq TRS\leq 1500 \quad (11)$$

$$WS: 20\leq WS\leq 60 \quad (12)$$

The primary population was presented in Table-3 and it represented the teacher phase. Individual intercepts for mechanical properties were calculated using equations (6) to (10). Based on the overall constraints (C^1) value (13), experiments were ranked.

$$C^1 = \left(\frac{C_{TS}}{(C_{TS})_{max}}\right) + \left(\frac{C_{YS}}{(C_{YS})_{max}}\right) + \left(\frac{C_{EL}}{(C_{EL})_{max}}\right) + \left(\frac{C_{IS}}{(C_{IS})_{max}}\right) + \left(\frac{C_{H}}{(C_{H})_{max}}\right) \quad (13)$$

The difference_ means of TRS and WS were calculated using equation (14) in the first rank experiments with process variables, which required the creation of new objective values and new process parameters to obtain constraint values with a random numbers [10]. The random numbers for the input parameters were chosen as 0.9 and 0.8, respectively and the difference_means is calculated as follows:

$$Difference\_mean = RX(x-y) \quad (14)$$

where R is a random number, x is the process parameter, and y is the mean of the process parameter.

Difference mean for TRS = 0.9 X (700-900) = - 180,

Difference mean for WS =0.8 X (20-60) = - 8.

To get a new process variable for the further experiments, the difference_values are added to the initial process variables and the values are added in the following presented as follows:

TRS = 700 + (-180) = 520.

WS = 30 + (-8) = 22.

Similarly, new process variables have been computed for all experiments and for all of the responses of output parameters. Again using the equations (1) to (5) for the SQ tool pins in Table 3, the values C_{TS}, C_{YS}, C_{EL}, C_{IS}, C_{H}, and C^1 were calculated using new response values and ranking the experiments. Based on the new process, parameters and the corresponding responses are presented in Table 4; one of the best combinations is obtained with 920 rpm of TRS and 42 of mm/ min WS. For further optimization of process parameters, the initial solution and the updated solution are included in Table 5. It is also known as a combined population. Then, the experiments were ranked based on the C^1 value. Based on rank, nine experiments were selected from Table 5 for further optimization of process parameters. At this stage, the experiments were treated as students in a class and allowed students to transfer knowledge from the best students to the lower ranked students to improve the overall performance of the class. Table 6 shows the teacher phase of the SQ tool pin. From Table 6, it can be seen that the best combination with 900rpm of TRS and 40 mm/min of WS is obtained from the initial solution. To obtain a better solution, interactions between experiments can be performed randomly [14]. Since the objectives of the present study are to increase H, IS, EL, YS, and TS, knowledge should be transferred from the best student to the next best student. The next best student can be chosen at random. Now, Studies Interactions between 1 and 9, 2 and 8, 3 and 7, 4 and 6, 5 and 1, 6 and 2, 7 and 3, 8 and 4, 9 and 5 using Eq.(15) and (16):

$$\text{New TRS} = \text{TRS1} + \text{R1}\,(\text{TRS1} - \text{TRS9}) \tag{15}$$

$$\text{New WS} = \text{WS1} + \text{R1}\,(\text{WS1} - \text{WS9}) \tag{16}$$

Where R1 and R2 are random numbers, they are chosen as 0.7 and 0.6 for the process parameters, respectively. Table 7 shows the new values of the process parameters after the interaction between the experiments and their reactions. All experiments were re-ranked. After negotiation, another best combination of process parameters such as 934 rpm of TRS and 20mm/min of WS is obtained. To obtain the best possible combination, the teachers 'phase, as well as the learners' stage, are presented in Table 8 for further processing. All experiments were re-ranked based on C^1 values.

From Table 8, the best combination of process parameters is chosen, in the first place, as the optimal combination of process parameters. The optimal combinations with their corresponding responses are presented in Table 9. Table 9 presents the optimal combinations of process parameters. Based on these combinations, setup experiments were carried out to validate the process.

Table 3. The initial population of SQ profile of teacher phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1
700	30	158.29	90.88	10.52	10.00	77.89	101.71	140.12	7.48	8.00	32.11	4.29
700	40	171.71	108.78	12.47	12.02	86.84	88.29	122.22	5.53	5.98	23.16	3.42
700	50	171.39	105.94	13.13	13.30	84.79	88.61	125.06	4.87	4.71	25.21	3.34
900	30	205.39	156.22	15.09	13.11	91.49	54.61	74.78	2.91	4.89	18.51	2.32
900	40	212.07	167.06	14.98	14.34	98.94	47.93	63.94	3.02	3.66	11.06	1.83
900	50	205.01	157.16	13.59	14.82	95.39	54.99	73.84	4.41	3.18	14.61	2.13
1100	30	194.17	158.84	8.62	7.82	78.45	65.83	72.16	9.38	10.18	31.55	3.77
1100	40	194.11	162.62	6.46	8.26	84.40	65.89	68.38	11.54	9.74	25.60	3.66
1100	50	180.31	145.66	3.01	7.94	79.35	79.69	85.34	14.99	10.07	30.65	4.34

Table 4. The Updated parameters of SQ profile of teacher phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1
520	22	40.55	-55.89	-7.01	-2.72	26.71	219.45	286.89	25.01	20.72	83.29	10.50
520	32	71.03	-15.04	-2.17	0.62	45.81	188.97	246.04	20.17	17.38	64.19	8.67
520	42	87.77	5.06	1.37	3.22	53.91	172.23	225.94	16.63	14.78	56.09	7.61
720	22	145.53	71.55	9.15	8.59	65.49	114.47	159.45	8.85	9.41	44.51	5.16
720	32	169.27	105.33	11.92	11.14	83.09	90.73	125.67	6.08	6.86	26.91	3.71
720	42	179.27	118.38	13.41	12.93	89.69	80.73	112.62	4.59	5.07	20.31	3.03
920	22	192.19	136.26	14.26	11.50	77.62	67.81	94.74	3.74	6.50	32.38	3.24
920	32	209.19	162.99	14.98	13.25	93.72	50.81	68.01	3.02	4.75	16.28	2.16
920	42	212.45	168.98	14.41	14.25	98.82	47.55	62.02	3.59	3.75	11.18	1.87

Table 5. The Combined population of SQ profile of teacher phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1	Rank
700	30	158.29	90.88	10.52	10.00	77.89	101.71	140.12	7.48	8.00	32.11	4.29	13
700	40	171.71	108.78	12.47	12.02	86.84	88.29	122.22	5.53	5.98	23.16	3.42	9
700	50	171.39	105.94	13.13	13.30	84.79	88.61	125.06	4.87	4.71	25.21	3.34	8
900	30	205.39	156.22	15.09	13.11	91.49	54.61	74.78	2.91	4.89	18.51	2.32	5
900	40	212.07	167.06	14.98	14.34	98.94	47.93	63.94	3.02	3.66	11.06	1.83	1
900	50	205.01	157.16	13.59	14.82	95.39	54.99	73.84	4.41	3.18	14.61	2.13	3
1100	30	194.17	158.84	8.62	7.82	78.45	65.83	72.16	9.38	10.18	31.55	3.77	12
1100	40	194.11	162.62	6.46	8.26	84.40	65.89	68.38	11.54	9.74	25.60	3.66	10
1100	50	180.31	145.66	3.01	7.94	79.35	79.69	85.34	14.99	10.07	30.65	4.34	14
520	22	40.55	-55.89	-7.01	-2.72	26.71	219.45	286.89	25.01	20.72	83.29	10.50	18
520	32	71.03	-15.04	-2.17	0.62	45.81	188.97	246.04	20.17	17.38	64.19	8.67	17
520	42	87.77	5.06	1.37	3.22	53.91	172.23	225.94	16.63	14.78	56.09	7.61	16
720	22	145.53	71.55	9.15	8.59	65.49	114.47	159.45	8.85	9.41	44.51	5.16	15
720	32	169.27	105.33	11.92	11.14	83.09	90.73	125.67	6.08	6.86	26.91	3.71	11
720	42	179.27	118.38	13.41	12.93	89.69	80.73	112.62	4.59	5.07	20.31	3.03	6
920	22	192.19	136.26	14.26	11.50	77.62	67.81	94.74	3.74	6.50	32.38	3.24	7
920	32	209.19	162.99	14.98	13.25	93.72	50.81	68.01	3.02	4.75	16.28	2.16	4
920	42	212.45	168.98	14.41	14.25	98.82	47.55	62.02	3.59	3.75	11.18	1.87	2

Table 6. The collective population based on the rank of SQ profile of teacher phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1	Rank
900	40	212.07	167.06	14.98	14.34	98.94	47.93	63.94	3.02	3.66	11.06	1.83	1
920	42	212.45	168.98	14.41	14.25	98.82	47.55	62.02	3.59	3.75	11.18	1.87	2
900	50	205.01	157.16	13.59	14.82	95.39	54.99	73.84	4.41	3.18	14.61	2.13	3
920	32	209.19	162.99	14.98	13.25	93.72	50.81	68.01	3.02	4.75	16.28	2.16	4
900	30	205.39	156.22	15.09	13.11	91.49	54.61	74.78	2.91	4.89	18.51	2.32	5
720	42	179.27	118.38	13.41	12.93	89.69	80.73	112.62	4.59	5.07	20.31	3.03	6
920	22	192.19	136.26	14.26	11.50	77.62	67.81	94.74	3.74	6.50	32.38	3.24	7
700	50	171.39	105.94	13.13	13.30	84.79	88.61	125.06	4.87	4.71	25.21	3.34	8
700	40	171.71	108.78	12.47	12.02	86.84	88.29	122.22	5.53	5.98	23.16	3.42	9

Table 7. The New process variables after the interaction of SQ profile of learner's phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1
1040	40	199.96	161.47	10.21	11.30	88.63	60.04	69.53	7.79	6.70	21.37	2.93
1074	37	195.95	159.66	8.64	9.78	84.41	64.05	71.34	9.36	8.22	25.59	3.37
886	60	196.01	150.17	11.43	14.76	93.66	63.99	80.83	6.57	3.24	16.34	2.47
1040	40	199.96	161.47	10.21	11.30	88.63	60.04	69.53	7.79	6.70	21.37	2.93
1060	26	198.84	163.11	9.43	10.57	84.56	61.16	67.89	8.57	7.43	25.44	3.18
580	20	109.62	32.51	1.67	5.81	57.56	150.38	198.49	16.33	12.19	52.44	6.81
934	20	202.75	159.59	12.59	14.60	92.49	57.25	71.41	5.41	3.40	17.51	2.31
546	61	106.88	28.99	3.19	3.02	50.26	153.12	202.01	14.81	14.98	59.74	7.27
560	46	114.07	33.47	5.27	4.13	56.67	145.93	197.53	12.73	13.87	53.33	6.72

(Note: Red color indicates the values are crossed the boundary)

Table 8. The Combined solutions ofSQ profile of learner's phase

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1	Rank
900	40	212.07	167.06	14.98	14.34	98.94	47.93	63.94	3.02	3.66	11.06	1.83	1
920	42	212.45	168.98	14.41	14.25	98.82	47.55	62.02	3.59	3.75	11.18	1.87	2
900	50	205.01	157.16	13.59	14.82	95.39	54.99	73.84	4.41	3.18	14.61	2.13	3
920	32	209.19	162.99	14.98	13.25	93.72	50.81	68.01	3.02	4.75	16.28	2.16	4
900	30	205.39	156.22	15.09	13.11	91.49	54.61	74.78	2.91	4.89	18.51	2.32	6
720	42	179.27	118.38	13.41	12.93	89.69	80.73	112.62	4.59	5.07	20.31	3.03	10
920	22	192.19	136.26	14.26	11.50	77.62	67.81	94.74	3.74	6.50	32.38	3.24	12
700	50	171.39	105.94	13.13	13.30	84.79	88.61	125.06	4.87	4.71	25.21	3.34	13
700	40	171.71	108.78	12.47	12.02	86.84	88.29	122.22	5.53	5.98	23.16	3.42	15
1040	40	199.96	161.47	10.21	11.30	88.63	60.04	69.53	7.79	6.70	21.37	2.93	8
1074	37	195.95	159.66	8.64	9.78	84.41	64.05	71.34	9.36	8.22	25.59	3.37	14
886	60	196.01	150.17	11.43	14.76	93.66	63.99	80.83	6.57	3.24	16.34	2.47	7
1040	40	199.96	161.47	10.21	11.30	88.63	60.04	69.53	7.79	6.70	21.37	2.93	8
1060	26	198.84	163.11	9.43	10.57	84.56	61.16	67.89	8.57	7.43	25.44	3.18	11

580	20	109.62	32.51	1.67	5.81	57.56	150.38	198.49	16.33	12.19	52.44	6.81	17
934	20	202.75	159.59	12.59	14.60	92.49	57.25	71.41	5.41	3.40	17.51	2.31	5
546	61	106.88	28.99	3.19	3.02	50.26	153.12	202.01	14.81	14.98	59.74	7.27	18
560	46	114.07	33.47	5.27	4.13	56.67	145.93	197.53	12.73	13.87	53.33	6.72	16

Table 9. The optimum combination of process parameters of SQ profile

TRS	WS	TS	YS	EL	IS	H	C_{TS}	C_{YS}	C_{EL}	C_{IS}	C_H	C^1	Rank
900	40	212.07	167.06	14.98	14.34	98.94	47.93	63.94	3.02	3.66	11.06	1.83	1

5. VALIDATION OF OPTIMIZATION

In the present study, the TLBO suggested that the best combination is 900 rpm and 40 mm/ min. The optimization is valid with experimental results. This combination is already used according to DOE. Experimental results of mechanical properties are compared with TLBO estimated results.

6. CONCLUSIONS

The present study has proposed an optimization-based strategy to incorporate TLBO to improve mechanical properties and the effect of various tool pin profiles on the mechanical properties of copper friction stir welds was also studied.

The main conclusions were drawn as follows:

• Square pin profile results better mechanical properties than other tool pin profiles due to greater pinning action.

• Defect-free welds were obtained for various tool pin profiles.

• The proposed methodology suggested the best combination for the SQ pin profile as 900 rpm of TRS and 40 mm / min of WS.

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