SELECTION AND OPTIMIZATION OF PROCESS PARAMETERS OF FRICTION SURFACED DEPOSITS

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Abstract: *Friction surfacing is the novel process used for the surface modification process. In this process, frictional heat generated during relative motion of two contact surfaces is used for deposition of one material over the other effectively. The amount heat required for joining is mainly depends on selection of process parameters such as friction pressure, rotational speed of consumable, welding speed and dwell period. In this paper, discussed the various process parameters and the factors considered in selection their levels. The optimum parameters of the deposit are determined by designing 2^3 experiments for obtaining the desired characteristics i.e., with three factors at two levels for each and measured the responses of each deposit. Performed primary inspection and regression equations are determined for each response such as surface roughness, width, height and bond strengths viz tensile strength and shear strength. Experimental work of friction surfacing is also performed and inspected the quality of the deposit.*

Keywords: *Friction Surfacing, Interface Properties, Friction Deposits, Process Parameters, Optimization, Solid State Welding.*

1. INTRODUCTION

Friction surfacing is a novel type of friction welding process which is a solid phase welding technique by means of which similar and dissimilar metals can be layered over the other effectively. In process, the parts are subjected to move relative to another under pressure so that the frictional heat developed at the interface between faying surfaces. The generated heat is utilized to join similar or dissimilar metals. This process is easily controllable, repeatable, reliable and is a simple machine tool technology, having similar benefits like other solid phase welding processes. The deposit is free from porosity, slag inclusions or dilutions which are generally experienced in traditional fusion welding processes. The process itself is environmentally clean, with no fumes, spatter or high intensity light emissions as in laser-based coating methods, hence it also termed as green manufacturing technology. Heat affected zone is comparatively less and hence post weld treatment process is not normally required to relieve internal stresses. This process can be performed in open air, with inert gas or under water [1-4]

In friction surfacing process, the consumable is in the form of a solid cylindrical and is rotated at a fixed speed. It is advanced under axial load on

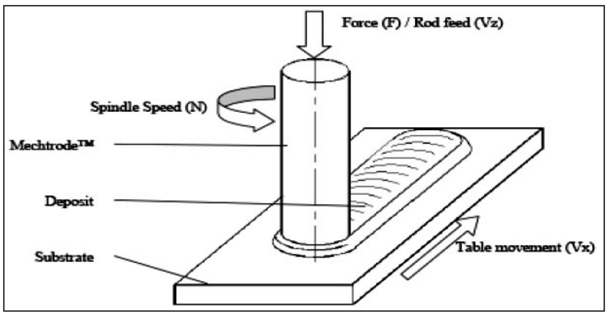


Fig 1.1. Principle of Friction Surfacing

to the substrate that causes the frictional heat at interface between faying surfaces. When forging temperature is reached, the substrate is moved with a fixed feed and certain percentage of plastic state is deposited over substrate with sufficient strength. The torque-time characteristics are important for the quantum of heat generated. Thickness, width, surface roughness and bond qualities depend on the parameters such as, friction pressure, rotational speed of consumable rod and transverse speed of substrate material and hence are called critical process parameters. Figure 1, shows the schematic diagram of process and process parameters involved in friction surfacing [5-10].

1.1 Materials Combinations

Friction surfacing is used to join a wide range of similar and dissimilar materials such as, aluminum and its alloys over steels, stainless steel over mild steel, hard facing of cutting edges deposits over steels, intermetallics, MMC (metal matrix composite) and many of the dissimilar metal combinations that cannot be joined by conventional fusion welding techniques [11-13]. Both brass and aluminum consumables fail to form a heated layer in contact with the mild steel due to high thermal conductivity of either metal [14].

2. SELECTION OF PROCESS PARAMETERS

In friction surfacing process, the consumable rod is rotated at a fixed speed and advances the same under axial load on to the substrate that causes the frictional heat at interface between faying surfaces. The heat generation at the interface line depends on the coefficient of friction between contacting surfaces, friction pressure, rotational speed and the rod diameter. The amount of heat liberated per unit area is by converting kinetic energy is given by $Q_{/}A = 2/3 \times PV_{max}$, Where Q = Heat energy, A = area of cross section of rotating consumable in mm^2, P =friction pressure (MPa), V_{max} = maximum velocity at the outer periphery of the consumable rod (mm/s).

The coefficient of dry friction is of 0.8 and greasy frictions 0.16 are taken for stainless steel and low carbon steel substrate. Since stainless steel has less thermal conductivity k_2 than the low carbon steel k_1. Hence more heat is dissipated towards stainless steel compared to low carbon steel. The partition ratio(r) of heat energy can be calculated by the relation $k_{1/}$ (k_1+k_2). From this ratio, it is expected that 71% of the heat generated at the interface would transfer heat into the low carbon steel and 29% into the stainless steel. Dwell time for initial rubbing time of 5 seconds. The quantity of heat energy required to heat the material to a forging temperature is obtained from the fundamental equation $[Q_1] = m\ s\ \Delta T$, Where, m = mass of the material being heated (in Kg), s = specific heat (KJ), ΔT = (forging –room) temperature. Hence, for a given diameter of mechtrode, required heat energy $(Q_1) = \rho \times A \times h \times s \times \Delta T /1000000$. Where, ρ = density in Kg/m^3, A = circular area in contact with substrate (mm^2) and h = expected height of the consummate to get plastic state (mm).

The quantity of heat generated is related to the power (P) consumed in friction surfacing and it is obtained by the relation, $P = 2\ \Pi\ N\ T /60$. Since the amount of power consumed in friction surfacing is utilized to raise the temperature of the consumable rod and substrate and hence

$(P) = 2\ \Pi N\ T/60 = 2\ \pi\ N\ (2/3\mu FR) / (60 \times 1000)$, [max. heat is generated at $2/3^{rd}$ radius]

$= 2\ \pi\ N(2/3)\mu\ (pA)R \times 9.8\ /(60 \times 1000)$, where p is the pressure in N/mm^2

$= (2/3)\ \mu AR\ [P \times N] / 1000$

But the amount of heat consumed by the mechtrode is equal to the 1/3 of the heat generated at the interface. At the initial the contact surfaces are having dry friction of coefficient of 0.8 and later greasy to 0.16 because of formation of plasticity. Hence the average value of coefficient of friction becomes at the contact surfaces to ½ (for simplification) for the dwell time of 5 seconds. The modified equation for the amount of heat utilized for heating the mechtrode nearer to its melting point can be written as $Q_1 = (\ P/2)*5\ /3$. But the amount of power consumed to heat the materials i.e. $Q_1 = P$. The amount of heat generated, when the dry friction present between contact surfaces is enough to raise the temperature to nearer to melting point, for the dwell time is taken as 5 seconds.

Hence $(\rho \times A \times h \times s \times \Delta T) /1000000 = 2/3\ \mu AR\ [P \times N]/1000$

$\Rightarrow [p \times N] = 3 \times (\rho s \Delta T) \times h /\ 2000 \times (\mu) \times R$

$\Rightarrow [p \times N] = C \times h/R$, Where 'C' is a constant for a given material.

Hence for a given material, the above equation can be written as, $(p_1 N_1 R_1) / h_1 = (p_2 N_2 R_2) / h_2$, Where p_1 and p_2 are the frictional pressures at minimum and maximum levels respectively. For Stainless Steel, Density = 7850 Kg/m^3, Specific Heat = 0.502 KJ/˚C, ΔT = 1263 and μ = 0.8. Substituting the above values for determining the value of C, the equation 'A' for Stainless Steel becomes p × N = (9295) h/R. Thus the height of the material to get plastic state per sec before substrate moves can be calculated for a given diameter of the consumable rod.

2.1. Determining Thickness of Coating

The volume of material heated = [π/4] × D^2 ×h, and the volume of material deposited is on substrate = 0.8 D× V_x × t, Where, h=height of the material heated at forging temperature, D = diameter of the consumable, V_x =distance traveled by substrate in X-direction (welding speed) and t=thickness of the weld Percentage of the material deposited = (0.8d × Vx × t × 100) / Π/4×d^2×h., which is equal to 4.0 % of the material being changed to plastic state.

Therefore (0.8d×Vx×t) / (Π/4×d^2×h) = 0.04 x (Π/4×d^2×h)

t = 0.04 x (Π/4×d^2×h)/ ((0.8d×Vx) = 0.04 x d x h / V_x

For the 15 mm diameter of the Stainless Steel rod used, the thickness of the coating (t) deposited is equal to 3.5h/V_x From this mathematical relation it is concluded that the inter-metallic layer thickness, i.e. deposit thickness is proportional to the product of the pressure and surface speed and inversely proportional to the traverse speed.

2.2. Guide Lines for Selection of Process Parameters

The selection of the above process parameters depends on the following factors i) forging strength of the consumable rod ii) coefficient of friction between the consumable rod and substrate, iii) diameter of the mechtrode and iv) physical and mechanical properties of consumable rod and substrate. The range of process parameters based on the metallurgical considerations like formation of intermetallic compounds due to diffusion phenomena between consumable rod and substrate. The physical properties of particular material combination like thermal conductivity and specific heat also influence the range of process parameters.

2.2.1 Selection of Friction Pressure

The amount of heat generated is a function of the friction pressure and rotational speed of the consumable rod, if the friction pressure is too high, there is chance of bending of the mechtrode, hence forging strength is important to fix the upper level of the friction pressure value.

2.2.2 Selection of Rotational Speed of the Mechtrode

The temperature at the interface of the mechtrode required nearer to the melting point of the mechtrode to obtain high bond strength and good coating integrity. Since the upper limit of the friction pressure is based on the forging strength of the selected materials and the corresponding lower level of the rotational speed is determined.

2.2.3 Selection of Welding Speed

Welding speed influences more on the coating thickness than the coating width. From the literature it is found that nearly 0.4% stainless steel and 0.2% of the tool steel M2, which heated plastic state is deposited on low carbon steel during friction surfacing. The width of the deposit is varying with process parameters selected, but its average value is nearer to 0.8 times the diameter of stainless steel and 0.6 times the diameter of tool steel used. It is also observed that the maximum deposit thickness is stainless less steel is nearer to 3 mm and 2.75 mm tool steel, but it depends on the materials to be deposited. If the welding speed is high, height of the deposit is decreased and therefore fixes the lower level and upper level of the welding speed to get 1-3 mm of stainless steel and 1-3 mm tool steel thickness of the deposit.

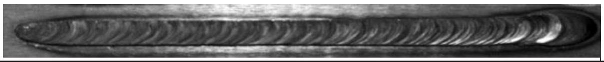
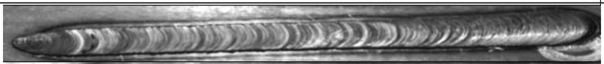
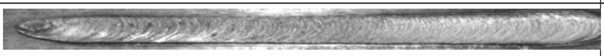
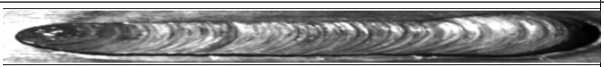
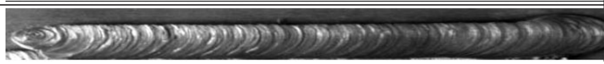
2.2.4 Dwell Time

Dwell time of 5 seconds is selected for stainless steel and 30 seconds tool steel for deposition over low carbon steel which is sufficient to obtain the mechtrode end to reach plastic stage. From the literature survey, the lower and upper levels of parameters are determined for getting thickness of 1-3 mm thickness of stainless deposit and 1-3 mm of tool deposit over low carbon steel. Upper and lower levels of process parameters are estimated by the mechanical and thermal properties of the materials. The parameters used for experimental work are shown in table 2 and table 3 for stainless steel and

Table1: Parameters Used for Deposition of Stainless Steel on Mild Steel

S. No	Factors	Notation	Unit	Level	
				Minimum (-1)	Maximum (+1)
1	Friction pressure(P)	X_1	MPa	26	49
2	Rotational speed of the mechtrode (N)	X_2	rpm	1400	2500
3	Welding speed (V_s)	X_3	mm/min	78	190

Table 2: Process Parameters Used for Deposition of Stainless Steel on to Low Carbon Steel

TC	Process Parameters			Deposition of SS over the LCS
	Friction pressure	Speed of mechtrode	Welding speed (mm/min) X_3	
1	26	1400	78	
2	49	1400	78	
3	26	2500	78	
4	49	2500	78	
5	26	1400	190	
6	49	1400	190	
7	26	2500	190	
8	49	2500	190	

tool steel respectively.

Three process parameters and two levels are identified according to the above calculations, for deposition of stainless steel deposit over the low carbon steel by friction surfacing and these values are shown in table 1.

Statistical design of experimental approach is ideally suited to minimize the number of trials required to optimize the welding conditions and finding the effects of interaction and effect of process parameters on the quality of the deposit. This experiment is carried out by using the 2^3 factorial designs i.e. with three factors at two levels for each. The experimental design matrix indicating these eight treatment combinations (TC) are shown in Table 2.

3. EXPERIMENTAL TRAILS ON FRICTION SURFACING MACHINE

15 mm diameter of 304 stainless steel and 10.5 mm diameter of tool steel M2 rods are made to 290 mm length pieces and used as consumable to deposit over the low carbon steel, termed as substrate by friction surfacing. The experimental work is conducted at Metal Joining Group, DMRL Hyderabad on a friction surfacing machine.

3.1 Deposition of Stainless Steel Over Low Carbon Steel

This experiment is carried out using the 2^3 factorial designs i.e., with three factors at two levels for each. Experimental design matrix indicating these eight treatment combinations (TC) are given in table 2.The process parameters as per treatment combination are set on the computer of the machine. With well time of 5 seconds the eight treatment combinations are completed as per the table and test specimens are made for investigation.

3.2. Deposition of M2 Tool Steel Over Low Carbon Steel

Using the eight treatment combinations indicated in table 3, for tool steel M2 consumable is deposited on low carbon steel and test specimens are made ready for investigation. After each trail, primary tests are conducted to the deposit whether the tool steel M2 is having bond with low carbon steel.

4. TESTING DEPOSITS

These tests are conducted on the shop floor after completion of each of the trails. The deposit is visually inspected for the physical appearance and any damage occurred. The adhesion tests such as lifting, chisel and hammer test, and grinding wheel tests are conducted, and the obtained results are found to be satisfactory. The evaluation of the quality of the deposit is broadly classified into non destructive testing and destructive testing. Non destructive testing plays a vital role in industry for quality control.

4.1. Non Destructive Testing (NDT)

Non-destructive testing methods have limitations for testing friction surfaced deposits. Surface defects like cracks, voids etc can be detected by visual and dye-penetrant examination. Hence ultrasonic test not preferable when dry penetrating is using. Radiography technique is normally best suited for the detection of the volumenar kind of defects.

4.2. Destructive Testing

In destructive testing the certain specific characteristics of the material can be evaluated quantitatively. Since the specimen is destroyed or mechanically changed. Shear strength and ram tensile strength tests are performed the evaluation of mechanical properties of bond quality [21-22].

4.3 Measurement of Responses of Friction Surface Deposits

4.3.1 Physical Responses

The physical characteristics/responses of the deposit such as width, height and surface roughness are measured at eight different locations and their average value is determined. This average value is taken as value of that response for that deposit.

4.3.2 Measurement of Mechanical Properties

The specimens are prepared from the deposits of all treatment combinations based on the standard ASTM 264 to calculate their shear strengths. Ram tensile test is used to determine the tensile strength of the bond. The specimens used for shear and ram tensile strength are shown in table 4. The same procedure is repeated for the stainless steel and tool steel M2 deposit over low carbon steel and the values are tabulated in Table 5 and 6 respectively.

Table 3: Selected Process Parameters for Friction Surfacing

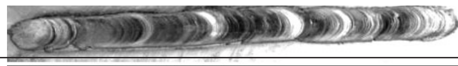
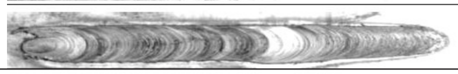
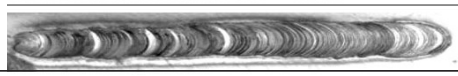
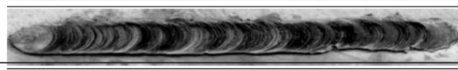
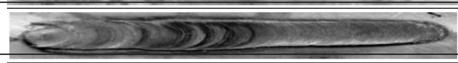
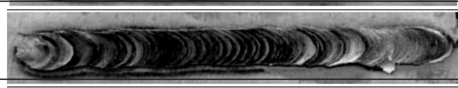
TC	Process parameters			Tool steelM2 Deposits
	Friction pressure	Rotational speed	Welding speed	
1	6	120	42	
2	12	120	42	
3	6	310	42	
4	12	310	42	
5	6	120	65	
6	12	120	65	
7	6	310	65	
8	12	310	65	

Table 4: The Specimens Used for Shear and RAM Tensile Strength Test

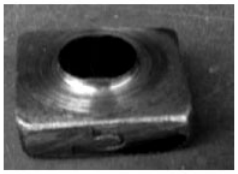
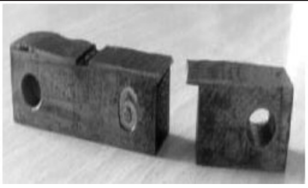
	Shear strength test		Shear strength test	
Deposit	**Specimen before test**	**Specimen after test**	**Specimen before test**	**Specimen after test**
Stainless steel deposit				
Tool steel M2 deposit				

Table 5: Responses Values of Stainless Steel Deposit Over Low Carbon Steel

TC	Responses				
	1	2	3	4	5
	Width (mm)	Height (mm)	Surface roughness (μ)	Shear strength (MPa)	Tensile strength (MPa)
1	10.9	1.4	6.82	72.5	297
2	12.45	2.6	2.63	85	426
3	11.52	1.5	6.25	156	656
4	14.15	1.6	1.94	155	448
5	10.44	1.1	6.10	172	518
6	12.47	1.2	7.83	162	484
7	10.76	0.9	6.65	350	312
8	13.25	1.5	9.68	150	360

4.3.3. Analysis of Deposit by using Regression Equations

The results (responses) of the stainless steel and tool steel M2 deposits over low carbon steel obtained by using eight treatment combinations are analyzed by using Taguchi quality approach. The regression equations for the responses are determined and shown in tables 7 and 8.

5. RESULTS AND DISCUSSIONS

Special purpose friction surfacing machine is most suitable and is advisable for effective control of process parameters with properly selected set of process parameters. Friction surfacing is capable of producing high quality joints between most dissimilar metal pairs.

Selection of process parameters for friction surfacing process for the given combination of materials plays crucial role in the protection of the machine, bond strength, coating quality and specific applications of the deposit. But there is limitation of higher friction pressure, due to mechtrode bending at the forging temperature. Increasing the rotational speed of the rod results in huge power consumption at initial stage and also stalls the motor, and sometimes the machine spindle subjected to vibrations.

The value of the width is not same for all eight treatment combinations and lies between 2/3 to 3/4 of the diameter of stainless steel consumable and nearly 2/3 of tool steel. These values are depend upon the process parameters used in the friction surfacing. From the regression equation, it is found that the deposits width is directly

Table 6: Responses Values of Tool Steel Deposit Over Low Carbon Steel

TC	Responses of the tool steel deposit				
	1	2	3	4	5
	Width (mm)	Height (mm)	Surface roughness (μ)	Tensile Strength (MPa)	Shear Strength (MPa)
1	11.6	1.35	6.52	61.01	25.16
2	12.42	2.54	2.43	129.39	55.08
3	11.32	1.45	6.15	67.20	25.13
4	13.85	1.55	1.84	122.66	49.25
5	10.24	1.12	6.05	67.13	28.51
6	12.27	1.23	7.63	62.42	24.53
7	10.76	0.95	6.55	158.32	75.62
8	13.05	1.53	9.48	138.62	61.65

Table 7: The Regression Equations for the Responses Stainless Steel Deposit Over Low Carbon Steel

S. No	Response	Regression Equations (Eliminated least significant terms)
1	Width	$y=11.9925+1.0875X_1+0.4275X_2-0.2625X_3+0.1925X_1X_2$
2	Height	$y=1.475+0.25X_1-0.075X_1X_2-0.3X_3+0.2X_1X_2X_3$
3	Surface Roughness	$y=5.9875-0.4675X_1+1.5775X_3+1.6575X_1X_3+0.4575X_2X_3$
4	Tensile strength	$y=437.625-31.875X_1X_2-19.125X_3-88.875X_2X_3+52.375X_1X_2X_3.$
5	Shear strength	$y=162.8125-24.8125X_1+39.9375X_2-25.4375X_1X_2+45.6875X_3-27.6875X_1X_3$

Table 8: Regression Equations for the Responses Tool Steel Deposit Over Low Carbon Steel

S. No	Response	Regression Equations (Eliminated least significant terms)
1	Width	$y=11.9387+0.95875X_1+0.30625X_2-0.35875X_3+0.24625X_1X_2$
2	Height	$y=1.465+0.2475X_1-0.2575X_3+0.1275X_2X_3+0.195X_1X_2X_3$
3	Surface Roughness	$y=5.83125-0.48625X_1+1.59625X_3+1.61375X_1X_3+0.41375X_2X_3+0.19625X_1X_2X_3$
4	Tensile strength	$y=100.8425+12.43X_1+20.8575X_2-18.5325X_1X_3+20.99X_2X_3$
5	Shear strength	$y=43.11625+4.51125X_1+9.79625X_2+4.46125X_3-8.99875X_1X_3+11.26125X_2X_3$

proportional to friction pressure and rotational speed.

The height of the deposit is proportional to friction pressure, inversely proportional to welding speed and interaction of friction pressure, rotational speed and welding speed. The surface roughness is directly proportional to friction pressure, inversely proportional to welding speed, combined effect of (i) friction pressure and welding.

The tensile strength is directly proportional to friction pressure and combined effect of friction pressure and welding speed. But inversely proportional to combined effect of friction pressure and rotational speed.

The shear strength is directly proportional to friction pressure, rotational speed and welding speed and combined effect of rotational speed and welding speed, and inversely proportional to combined effect of friction pressure and welding speed.

From the surface methodology, the optimum process parameters can be determined within the volume of the prism for obtain desired properties of the deposit.

Acknowledgements

The authors would like to thank Dr. G. Malakondaiah, Director, DMRL, Hyderabad, India and Dr. G. Madhusudhan Reddy, Head, of Metal Joining Group, Defense Metallurgical Research Laboratory, Hyderabad, India for their continued encouragement and permission to do experimental work. We also thank management, Director and Principal of Gokaraju Rangaraju Institute of Engineering and Technology and Institute of Aeronautical Engineering, Dundigal, Hyderabad for their encouragement and providing facilities for testing the deposit of this research work. The authors are grateful to principal of RVR & JC College of Engineering, Guntur and Andhra Pradesh for giving technical support completion of this research work.

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