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FINITE DIFFERENCE MODELING ON THE TEMPERATURE FIELD OF ALUMINIUM AND LOW CARBON STEEL IN FRICTION SURFACING

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ABSTRACT

Friction surfacing is an emerging surface engineering technology, an advanced process of great potential, especially in the field of repair and reclamation of worn and damaged components. The temperature field of Mechtrode (consumable rod) in friction surfacing, as a kind of thermal processing technology, is an important factor in the successful implementation of the process. In this work, the temperature model of mechtrode in friction surfacing is established. Using finite element method the temperature field of consumable-rod during the friction surfacing process is simulated. In this work low carbon steel (EN1A) is used as a Substrate Material and Aluminum 6061 Alloy is used as a Mechtrode. Mectrode rotation speed is varying from 900 to 1500 rpm and the axial load applied is 10 KN. The deformation on the mechtrode and temperature values is presented. Ansys software is used for this analysis.

Keywords: friction surfacing, finite element method, thermal field, al6061 mechtrode, low carbon steel substrate.

INTRODUCTION

Friction surfacing is a process derived from friction welding where a coating material is applied to a substrate. A rod composed of the coating material (called a mechtrode) is rotated under pressure, generating a plasticized layer in the rod at the interface with the substrate. By moving a substrate across the face of the rotating rod a plasticized layer is deposited between 0.2 to 2.5 millimeters (0.0079-0.098 in) thick depending on mechtrode diameter and coating material. Its typical process showed Figure-1. Friction surfacing is an advanced process of great potential, especially in the field of repair and reclamation of worn and damaged components. The temperature field of consumable rod in friction surfacing, as a kind of thermal processing technology, is an important factor in the successful implementation of the process. In this paper, the heat source model of consumable-rod in friction surfacing is established, by which the temperature field of consumable-rod during the process is simulated through finite difference method.

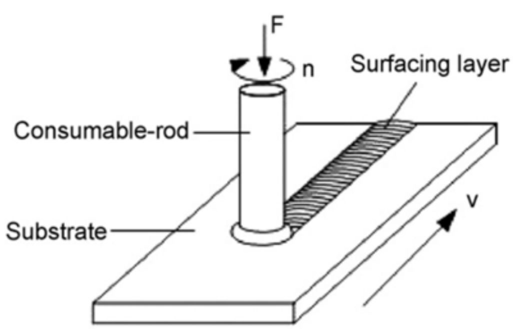

Figure-1. Friction surfacing process.

Many works focused the friction surface process with various materials and process parameters. Khalid Rafi *et al* [1] explained that the Tool steel H13 was friction surfaced on low carbon steel substrates. Mechtrode (consumable rod) rotational speed and substrate traverse speed were varied, keeping the axial force constant. The effects of process parameters on coating characteristics and integrity were evaluated. A process parameter window was developed for satisfactory deposition of tool steel coatings. Coating microstructures were examined using optical microscopy, scanning electron microscopy, and transmission electron microscopy. Micro hardness tests, shear tests, and bend tests were conducted on coatings. The results show that coating width is a strong function of mechtrode rotational speed, while coating thickness is mainly dependent on substrate traverse speed. Lower mechtrode rotational speeds results in wider coatings, while higher substrate traverse speeds produce thinner coatings. Thinner coatings exhibit higher bond strength than thicker coatings. Coatings show no carbide particles, yet exhibit excellent hardness (above 600 HV) in as-deposited condition due to their martensitic microstructure. V.I. Vitanov *et al* [2] have identified the relationships between the input variables and the process response and to develop predictive models that can be used in the design of new friction surfacing applications. Moreover to investigate the use of standard CNC machines for friction surfacing. The experimental design techniques and response surface methodology were used to investigate and select the combination of factor levels that produced the optimal response. The main effect of the velocity ratio obtained by dividing the feed rate of mechtrode with traverse rate of substrate was observed to be the most significant factor on the process response. Based on the results of optimization it was observed that the lower to intermediate levels of rotational speed and intermediate to higher levels of velocity ratio produced good coating quality. V.I. Vitanov [3] used the combined artificial intelligence and modeling techniques. It includes a new frame of a neurofuzzy-model based decision support system-*FricExpert*, which is aimed at speeding up the parameter selection process and to assist in obtaining values for cost effective development. Derived models can then be readily used for optimization techniques, discussed in their earlier work.

Heat source model has explained by many researchers. Xuemei Liua *et al* [4] explained that the Friction surfacing is an advanced process of great potential, especially in the field of repair and reclamation of worn and damaged components. The temperature field of consumable rod in friction surfacing, as a kind of thermal processing technology, is an important factor in the successful implementation of the process. In this paper, the heat source model of consumable-rod in friction surfacing is established, by which the temperature field of consumable-rod during the process is simulated through finite difference method. The results are consistent with experiments, re-appearing the temperature field of consumable rod during friction surfacing, thus providing theoretical guidance in the choice for key technical parameters in engineering practice. V.I. Vitanov, N. Javaid [5] investigated the thermal response of the micro friction surfacing process with complex geometries and to tackle transient deposition processes, suitable numerical methods have been developed. The approach of coupled transient thermal analysis to account for the temperature fields generated during the dwell and deposition phases of the process resulted in reasonably accurate results, with an error of 18% between absolute maximums. The major discrepancy between the experimental and simulated results occurred at locations with a change in substrate geometry. The heat distribution profile at the frictional interface and variation in material properties with temperature could have significant effects on the thermal response.

H. Khalid Rafi *et al* [6] made friction surfacing of Tool steel H13 on low carbon steel substrates. Mechtrode (consumable rod) rotational speed and substrate traverse speed were varied, keeping the axial force constant. The effects of process parameters on coating characteristics and integrity were evaluated. A process parameter window was developed for satisfactory deposition of tool steel coatings. Coating microstructures were examined using optical microscopy, scanning electron microscopy, and transmission electron microscopy. Micro hardness tests, shear tests, and bend tests were conducted on coatings. The results show that coating width is a strong function of mechtrode rotational speed, while coating thickness is mainly dependent on substrate traverse speed. Lower mechtrode rotational speeds results in wider coatings, while higher substrate traverse speeds produce thinner coatings. Thinner coatings exhibit higher bond strength than thicker coatings. Coatingsshow no carbide particles, yet exhibit excellent hardness (above 600 HV) in as-deposited condition due to their martensitic microstructure.

In recent years, researchers started to focus on the utilization of aluminum alloy bar for the coating layer and substrate. Hidekazu Sakihama [7] used 5052 aluminum alloy as substrate and consumable rod. Friction surfaced using a numerical controlled full automatic friction welding machine. Effects of the surfacing conditions on some characteristics of deposits were investigated. It was clearly observed that the circularly pattern appeared on the surface of deposit by the rotation of consumable rod. The deposit has a tendency to incline toward the advancing side further than center of deposit for the feed direction of consumable rod. This deviation accompanied the decrease of the rotational speed of consumable rod. The width of deposit increased with increasing friction pressure, and decreasing rotational speed of consumable rod. The thickness of deposit became thinner when the consumable rod was high revolution. The surfacing efficiency decreased with increasing friction pressure and rotational speed of consumable rod, but increased with increasing feed speed. Microstructure of the deposit was finer than that of the substrate and consumable rod. The softened area was recognized at 3mm distance from the weld interface of substrate. The tensile strength of deposit increased with increasing friction pressure. The maximum tensile strength of deposits showed 88.8% of the base metal of substrate. I. Voutchkov [8] discussed the procedures for data collection, management and optimization of the friction surfacing process. Experimental set-up and characteristics of measuring equipment are found to match the requirements for accurate and unbiased data signals. The main friction surfacing parameters are identified and the first stage of the optimization process is achieved by visually assessing the coatings and introducing the substrate speed. forcemap. The optimum values from this first stage forms a region around the middle of a trapezium-shaped area whose borders are found experimentally. Data collected for the second stage were analyzed using the least squares method which was applied to find the coefficients of a second order regression model. Advantages of applying artificial intelligence methods to friction surfacing modeling are also described and the higher accuracy achieved using neural networks demonstrated. Stefanie Hanke [9] investigated the coating layers of NiAl-bronze were deposited by friction surfacing on self-mating substrates, followed by micro structural characterization. Further, cavitations tests were performed in order to investigate wear resistance. Cavitation erosion mechanisms were analysed by means of optical and electron microscopy. All coatings show incubation periods about twice as longas those of the substrate material, while their average rate of material loss is about one half of that of the substrate. The differences in cavitation erosion resistance are due to more ductile behavior of the coatings, as well as corrosion increasing the wear of the as-cast material. G.M. Bedford [10] discussed with the friction surfacing of high-speed steels, BM2, BT15 and ASP30 onto plain carbon steel plate. The events that the matrix and carbides experience as the coating material pass from the coating rod to the substrate, in forming the coating, is described. The coating is observed to harden automatically within a few seconds of being deposited onto the cold substrate. This auto hardening is observed to be an inherent feature of the friction surfacing process and the

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only post-coating heat treatment required is tempering, as with traditionally hardened high-speed steels. The mechanism of auto hardening is discussed in terms of the mechtrode-coating-substrate thermal system. Dai Nakama [11] was performed Monolayer friction surfacing using a numerical controlled full automatic friction welding machine for AZ31 magnesium alloy plate used for substrate and AZ91 magnesium alloy casting bar used for consumable rod. Effect of the surfacing conditions on structures and mechanical properties of deposit were investigated. It was clearly observed that the circular pattern appeared on the surface of deposit by the rotation of coating rod. Microstructures of deposit showed finer structure than that of both base metals, and the cast structure was disappeared. Hardness of the deposit showed higher value than that of the substrate. Wear resistance of the deposit was improved in comparison with the substrate.

H. Khalid Rafi, N. Kishore Babu [12] deposited Austenitic stainless steel AISI 304 coating on low carbon steel substrate by means of friction surfacing. The micro structural evolution was studied. The micro structural characterization of the coating was carried out by optical microscopy (OM), electron backscattered diffraction (EBSD), and transmission electron microscopy (TEM). The coating exhibited refined grains (average size of 5 lm) as compared to the coarse grains (average size of40 lm) in as-received consumable rod. The results from the micro structural characterization studies show that discontinuous dynamic recrystallization (DDRX) is the responsible mechanism for grain evolution as a consequence of severe plastic deformation. S. Janakiraman [13] deposited Commercial pure aluminum on medium carbon steel using friction surfacing route. An aluminum rod was used as the consumable tool. Normal load and tool rotation speed were the variables. Under certain combinations of load and speed the deposition was continuous and uniform. The deposit consisted of Al embedded with fine particles of iron. The interface between substrate material and deposited material was smooth and relatively small. A mechanism is discussed for formation of a composite surface on the steel substrate.

Marcio Levi Kramer de Macedoa [14] presented the state of the art of deposition by means of the friction surfacing process, the influences of the deposition parameters and some applications of the process. In second part, some results for a study being conducted with deposition of three different consumable rods (materials for ABNT 8620, ABNT 4140, and AISI 310 steel rods) in substrate of ABNT 1070 carbon steel will be presented, using as deposit parameters a rotational rod speed of 3500 rpm, traverse speeds of 8.5-17 mm/s, and axial pressure of 1.03 and 1.38 MPa. The deposits were characterized by visual analysis, macrograph analysis, micrograph analysis, micro hardness profile, and push-off test. The results so far were considered to be satisfactory, showing that the technique can be employed to repair surfaces of components in high carbon steels and for deposition of similar and dissimilar materials. However, the optimum parameters for the process must still be studied. J. Gandra [15] addressed the deposition of AA 6082-T6 coatings on AA 2024-T3 substrates, while focusing on the effect of process parameters, such as, axial force, rotation and travel speed. Sound aluminum coatings were produced with limited intermetallic formation at bonding interface. It was observed that low travel and rotation speeds contribute to an increase of coating thickness and width. Bonding at coating edges deteriorates for faster travel speeds. The axial force is determinant in achieving a fully bonded interface. H. Khalid Rafi [16] explained the metal flow behavior within friction surfaced coating using tungsten powder as a marker. The results show that the top and bottom layers within the coating exhibit distinct flow patterns. The transport of material takes an involute path, and the material transfer starts from the advancing side of the coating to the retreating side and terminates at the center. The recirculation of material occurs at the retreating side of the coating. K. PrasadRao *et al* [17] reported a feasibility study on producing friction surfaced coatings on nonferrous substrates. Commercially pure aluminum, copper, magnesium (ZM21), Inconel800, and titanium alloy (Ti-6Al-4 V) were chosen as the substrates. Low carbon steel, aluminum alloy (AA6063), commercially pure copper and titanium were chosen as the consumable rods. Friction surfacing was attempted with all consumable rods on every substrate. In some cases metallurgical bonded coating was obtained readily over the substrate and in some other cases coating was obtained with a start-upplate. However, for certain combination of parameters, nocoating could be obtained. The coatings obtained were analysed for their micro structural features and interfacial characteristics using optical and scanning electron microscopy. The results showed that co-efficient of friction, material properties like thermal conductivity, and stability at high temperature influenced the formation of a coating. Coatings obtained exhibited fine grained microstructure with properties better than the original parent material. Dynamic recrystalization as a result of severe plastic deformation accounts for grain refinement.

In the present study, the finite difference method was employed to simulate the consumable-rod's temperature field. The temperature field in friction surfacing, especially of the consumable-rod, is considered an important element in analysing the process' mechanism and in the proper choice of key process parameters. The results from this study can provide theoretical guidance in analyzing the feasibility and choosing key parameters in similar endeavors.

HEAT SOURCE MODEL

The whole friction surfacing process is divided into two sequential phases:

1. Preliminary friction preheating phase
2. Steady surfacing phase.

Figure-2 shows the friction surfacing process with various parameters. At the beginning of the process, friction heat is employed as the main heat source. As the temperature increases, local regions at the end of the

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consumable-rod start to become plasticized. In these local regions, plastic deformation heat becomes the main heat source. The process is carried on as the plasticized regions continuously enlarge and until the whole friction interface becomes plasticized. By the end of the preliminary friction preheating phase, the main heat source shifts from friction heat to plastic deformation heat. By the end of the friction preheating phase, the consumable-rod's temperature field begins to achieve a quasi steady status. In the next surfacing phase, the temperature field retains its quasi-steady condition all through. So, the emphasis is laid on calculating the temperature field in the preheating phase.

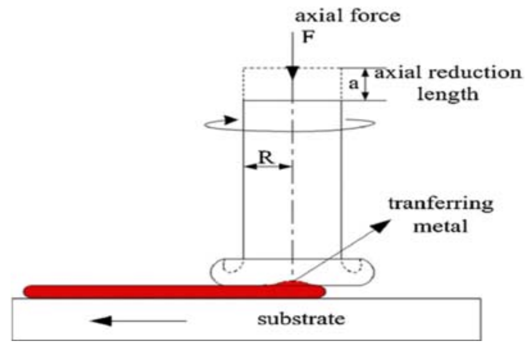

Figure-2. Process of friction surfacing.

MATERIALS

In this work Low carbon steel is used as the substrate (150X100X8) mm and Al 6061 alloy is used as mechtrode. The diameter of the mechtrode is 18 mm and the length is 100 mm.Table-1 shows the mechanical properties of the coating material and substrate.

Table-1. Properties of mechtrode and substrate.

SN	PROPERTIES	SUBSTRATE	MECHTRODE
1	Density	7.7 g/cm^3	2.70 g/cm^3
2	Young's modulus	190 GPa	70 GPa
3	Thermal conductivity	36 W/mk	237 W/mk
4	Melting point	1464^{0}C	660^{0}C
5	Poisson's ratio	0.3	0.35

PROCESS PARAMETERS

The quality of the coating is based on mechtrode rotational speed; axial load acting on the substrate, traverse speed and diameter of the mechtrode. Table-2 shows the process parameters used for this finite element analysis.

Table-2. Process parameters.

S. No	PROCESS PARAMETERS	VALUES
1	Mechtrode rotational speed	900, 1000, 1100, 1200, 1300, 1400, 1500
2	Axial load	10 KN
3	Travers speed	Constant

GEOMETRY AND PARAMETERS

For the Ansyssimulation, a 3-D model of mechtrode and substrate was designed in CATIA V5R17 and Ansys software was used for meshing. All the necessary boundary conditions were applied in Ansysthe Table-3 Shows the boundary conditions for the thermal analysis. In the symmetrical model, the computation was made in less time as the total number of mesh decreased compared to the full model. Whenever possible, Ansys suggests applying symmetry.

Table-3. Meshing condition.

S. No	GEOMETRY SECTION	Type: TETRAHEDRON MESH	
		No of Mesh Elements	No of Nodes
1.	Substrate	8456	16412
2.	Mechtrode	6525	12144

SIMULATION PROCEDURE

CATIA V5 R17 Software is used to model the substrate and mechtrode. The whole process, a non-linear FE model (using ANSYS 16.0) was developed. A combination of Tetrahedron elements is used for allMechtrode and substrate in order to handle their

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interaction. The mesh method that was adopted to simulate and solve the heat source model problem. An Advanced meshing was used to mesh the whole system. The main aim is to develop a fine mesh near the mechtrode surface in order to gain better accuracy in temperature profile.

SIMULATION OF THE MECHTROD'S TEMPERATURE FIELD

From the Previous Literatures we have select the mechtrode and substrate dimensions designed theFigure-3 shows the 3D meshed model of the Aluminium mechtrode with 10 KN axial load

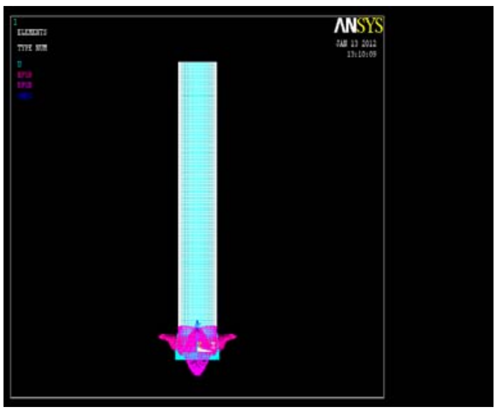

Figure-3. Meshed model of the mechtrode with load.

DEFORMED SHAPE OF MECHTRODE

For calculating deformation on the mechtrode due to axial load of 10KN load, the mechtrode deformed in the tip. Figure-4a, b shows the dynamic analysis on mechtrode and deformation values

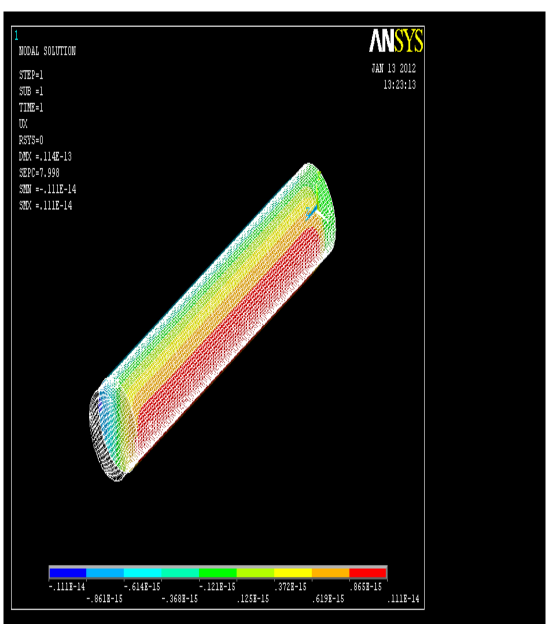

Figure-4(a). Deformation of Mechtrode.

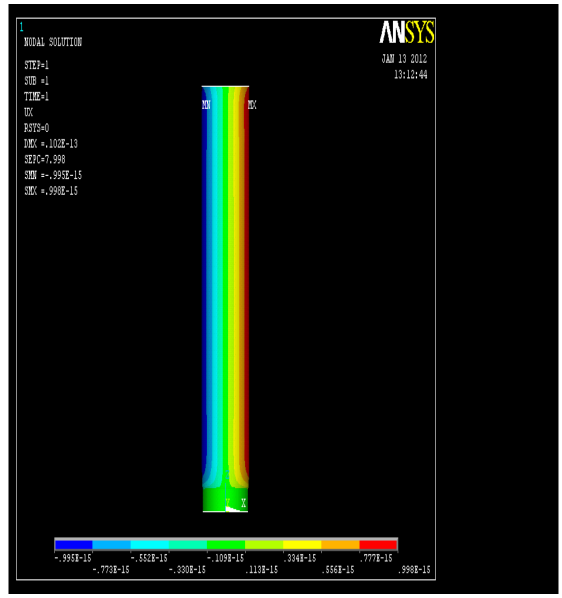

Figure-4(b). Deformation of Mechtrode.

TEMPERATURE FIELD IN MECHTRODE

Figure-5 illustrate the temperature field at the center Section of the consumable-rod at different rotational speed. Prior to the completion of friction preheating, in other words, at a time shorter than preheating time (e.g., 10, 20, and 30 s), the main heat source is generated through friction, and the temperature pro file along the radial direction represents. Consequently, when the temperature at the friction interface becomes sufficiently high, the material completely transforms into plastic, the stress field has likely become uniformed, and friction heat increases rapidly at the outer areas, such that the temperature profile along the radial direction represents. In this work we give different rotational force to the mechtrode (900, 1000, 1100, 1200, 1300, 1400, and 1500) rpm. Table-3 shows the simulation values for different rotational speeds. The optimum result we can get from 1500 rpm of the mechtrode rotational speed.

Table-4. Temperature field obtained from simulation.

SIMULATION RUN	MECHTRODE ROTATIONAL SPEED	HEAT FLUX
1	900	245.28
2	1000	375.13
3	1100	418.41
4	1200	483.84
5	1300	533.83
6	1400	591.55
7	1500	649.26

The Figure-5 shows the contour plot of the thermal field generated in the Al 6061 mechtrode in 1500 rpm.

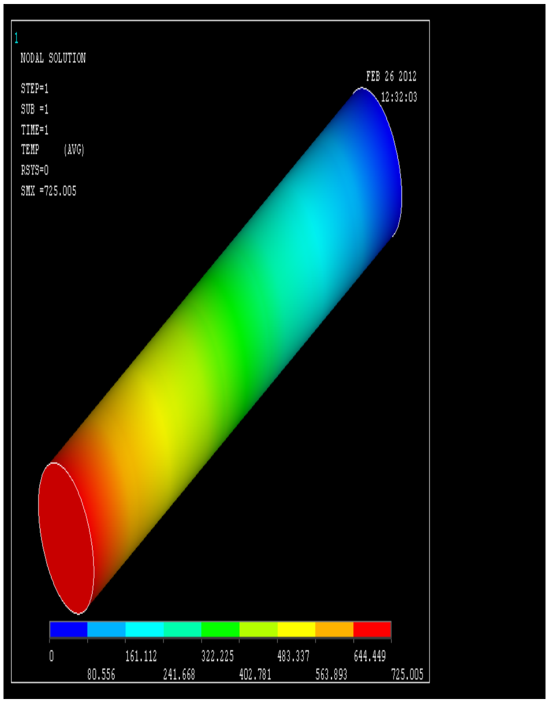

Figure-5. Temperature field of Aluminium at 1500 rpm.

CONCLUSIONS

The heat source model of Aluminum consumable rod was obtained using thermal analysis. Analysis results are compared with various rotational speeds ofmechtrode. From the results 1500 rpm is the best suitable rotational speed for aluminum while coating for low carbon steel substrate.

REFERENCES

[1] H. Khalid Rafi G.D. Janaki Ram, G. Phanikumar, K. Prasad Rao 2011. Micro structural evolution during friction surfacing of tool steel H13. Materials and Design, 32(1): 82-87.

[2] V.I. Vitanov, N.Javaid, D.J.Stephenson. 2010. Application of response surface methodology for the optimization of micro friction surfacing process. Surface and Coatings Technology. 204, 3501-3508.

[3] V.I. Vitanov, I.I. Voutchkov. 2005. Process parameters selection for friction surfacing applications using intelligent decision support. Journal of Materials Processing Technology 159, 27-32.

[4] Xuemei Liu, Junshan Yao, Xinhong Wang, ZengdaZou, Shiyao Qu. 2009. Finite difference modeling on the temperature field of consumable-rod in friction surfacing. Journal of materials processing technology.1392-1399.

[5] V.I. Vitanov, N. Javaid. 2010. Investigation of the thermal field in micro friction surfacing. Surface and Coatings Technology 204, 2624–2631.

[6] H. Khalid Rafi, G.D. Janaki Ram, G. Phanikumar, K. Prasad Rao. 2010. Friction surfaced tool steel (H13) coatings on low carbon steel: A study on the effects of process parameters on coating characteristics and integrity. Surface and Coatings Technology, 205, 232-242.

[7] HidekazuSakihama, Hiroshi Tokisue and Kazuyoshi Katoh.2003.Mechanical properties of friction surfaced 5052 aluminum alloy. Materials Transactions, Vol. 44, No. pp. 2688 to 2694.

[8] I. Voutchkov, B. Jaworski, V.I. Vitanov, G.M. Bedford. 2001. An integrated approach to friction surfacing process optimization. Surface and Coatings Technology 141. 26-33.

[9] Stefanie Hanke, Alfons Fischer, Matthias Beyer, Jorge dos Santos. 2011. Cavitation erosion of NiAl-bronze layers generated by friction surfacing. Wear. 273 (2011) 32-37.

[10] G.M. Bedford, V.I. Vitanov, I.I. Voutchkov. 2001. On the thermo-mechanical events during friction surfacing of high speed steels. Surface and Coatings Technology. 141, 34-39.

[11] Dai Nakama, Kazuyoshi Katoh, Hiroshi Tokisue. 2008. Some Characteristics of AZ31/AZ91 dissimilar magnesium alloy deposit by friction surfacing. Materials Transactions, Vol. 49, No. 5 pp. 1137 to 1141.

[12] H. Khalid Rafi, N. Kishore Babu, G. Phanikumar, K. Prasad Rao. 2012. Micro structural evolution during friction surfacing of austenitic stainless steel AISI 304 on low carbon steel" The minerals, metals and materials society and ASM International.

[13] S. Janakiraman, K. Udaya Bhat. 2012. Formation of composite surface during friction surfacing of steel with aluminum. Advances in Tribology, Volume 614278.

[14] Marcio Levi Kramer de Macedoa, Gustavo A. Pinheiro, Jorge F. dos Santos, Telmo R. Strohaecker.

2010. Deposit by friction surfacing and its applications. Welding International Vol. 24, 422-431.

[15] J. Gandra, D. Pereira, R. M. Miranda, P. Vila. 2013. Influence of process parameters in the friction surfacing of AA 6082-T6 over AA 2024-T3. Procedia CIRP.

[16] H. Khalid Rafi, G. Phanikumar, G. Prasad rao. 2011. Material flow visualization during friction Surfacing. Metallurgical and materials transactions, Volume 42a, 939.

[17] K. Prasad Rao, Arun Sankar, H. Khalid Rafi, G. D. Janaki Ram, G. Madhusudhan Reddy. 2012. Friction surfacing on nonferrous substrates: a feasibility study. International Journal of adv manufacturing technology.