SYNOPSIS OF THE Ph.D THESIS

Title of Thesis: Process Development for Surface Alloying of Bronze with Ni/Cr using GTA Heat Source - Modelling and Validation

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SYNOPSIS OF THE Ph.D THESIS

PROCESS DEVELOPMENT FOR SURFACE ALLOYING OF BRONZE WITH Ni/Cr USING GTA HEAT SOURCE - MODELLING AND VALIDATION

by

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1. INTRODUCTION

Bronze is commonly used as a bearing material in aircrafts, automobiles and industrial applications because of its superior wear property. In an effort to improve further its wear resistance, researchers have resorted to adding Ni so that the non-hardenable Bronze (Cu-Sn) becomes hardenable by a heat treatment method called ‘spinodal decomposition’. However, the tribological property need not be improved for the entire bulk of the alloy, rather it is sufficient for many applications if it is enhanced to a certain depth from the surface. It is to be noted that the bulk hardening, in general, decreases the toughness and therefore, the improvement of wear property confining to the sub-surface has an added advantage of keeping the core tough while reducing the addition of the expensive Ni. Since no research work has been reported previously in this regard, it is worthwhile to pursue the development of a process to make surface-modified Bronze.

Surface Allooying Process (SAP) has emerged recently as a method to enhance various surface properties of materials such as steel, superalloys, etc. In the SAP, the heat is applied by a suitable heat source over the substrate which is coated with an alloying element, resulting in melting and mixing of both the top surface of the substrate and the coating. As the heat source moves further, the molten zone solidifies and a modified surface layer to the entire length of the substrate is thus obtained. The geometry of the molten zone and the distribution of the alloying element into the substrate are the main factors that decide the wear property of the surface. Therefore, a reliable model combining both heat and mass transfer aspects to simulate the heating, melting, convection, mixing, and re-crystallization processes becomes mandatory in order to fully control the layer thickness and the solute distribution, thereby effectively characterizing the SAP.

2. SCOPE OF THE WORK

The scope of the present study centers around the development of (i) the SAP for the improvement of the tribological properties of bronze (Cu-Sn) with the addition of Ni/Cr, and (ii) simplified heat and mass transfer models to compute the geometry of the modified layer and the solute distribution within the substrate, respectively. In order to solve the heat transfer equation, the effective area of the heat application and the thermal efficiency are the two critical parameters that are required as functions of the process variables, in addition to the thermal and the physical properties of Bronze. In this study, the area, defined as the heat distribution parameter in the literature, is measured experimentally by using a vision-based technique and a parametric model relating the area to the process variables is constructed. The
thermal efficiency of the gas-tungsten arc (GTA) heat source employed in this study is
determined through a combination of experimental and simulation methods and a parametric
model relating the thermal efficiency to the process variables is also constructed. Further,
experiments are conducted to validate the heat and mass transfer models. The effect of Ni/Cr
content on the hardness of the modified layer is also evaluated and is compared with each
other.

3. ORGANIZATION OF THE WORK

The general scheme of the present work is as follows:

- Heat distribution parameters and efficiency are input to solve the heat transfer
equation so as to get the geometry and the temperature profile.
- The temperature profile is input to the mass transfer equation and is solved to obtain
the concentration profiles.
- The computed and the experimental concentration profiles were compared.
- The experimental data are further used to assess the effect of Ni/Cr on the hardness.

4. HEAT TRANSFER MODELLING

In SAP, the heat source (gas tungsten arc) moves over the substrate at a specified speed in the
horizontal direction with a well-defined power intensity. The surface of the substrate is melted
by the heat source and the alloying element is dissolved into the substrate due to convection
and diffusion. As the heat source moves further, the molten zone solidifies to form a modified
layer. During the process, the heat transfer occurs by conduction within the substrate, and the
heat is lost from the boundaries of the substrate through convection. This process is further
complicated by the convection occurring in the molten zone due to arc, magnetic and
buoyancy forces, and surface tension gradient, etc., [1]. In order to account for this convection
effect, researchers have adapted a method by which they have added an enhancement factor
to the thermal conductivity of liquid [2]. This method is followed in this study. Since the
process also involves solidification of molten metal, the latent heat of fusion is handled by
adding its value to the enthalpy of liquid.

4.1 Governing Equation

A simplified heat transfer model applicable to the above process is expressed as below:[3],
[4]

$$\rho c \frac{\partial T}{\partial t} = \rho c U \frac{\partial T}{\partial x} + \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)$$ (1)
where $k$: thermal conductivity (Wm$^{-1}$K$^{-1}$), $\rho$: density (kgm$^{-3}$), $c$: specific heat (Jkg$^{-1}$K$^{-1}$), $T$: temperature (K), $t$: time (s), $U$: velocity of the heat source (ms$^{-1}$) and $x, y, z$: coordinates.

The above equation can be solved using appropriate initial and boundary conditions. In order to evaluate Equation 1, the positional variation of the heat flux, $q(x,y)$, from the GTA source that is incident on the substrate is also required and it is expressed by a Gaussian distribution as below [5]:

$$q(x, y) = \frac{3\eta VI}{A_i} e^{-\frac{3x^2}{a^2}} e^{-\frac{3y^2}{b^2}}$$

(2)

where $\eta$: thermal efficiency of the heat source, $V$: voltage, $I$: current, $a, b$: heat distribution parameters, $A_i$: area of heat incidence. Since it is a double elliptical model, $a$ is taken to be $a_f$ and $a_r$ for the front and rear of the arc with its center at point ‘O’ (refer to Fig. 1), respectively.

**Figure 1.** Schematic of the GTA Surface Alloying Process

In this study, for evaluating $q(x,y)$, the required parameters, $a$ and $b$ are experimentally measured and $\eta$ is computed using a combined experimental and simulation method.

4.2 Measurement of Heat Distribution Parameters

Several studies have been conducted previously to estimate the heat distribution parameters of the arc viz. split anode calorimetric method, theoretical models (Genetic algorithm etc.,) and vision-based measurement and in some instances, the weld pool width itself was taken to be the heat distribution parameters [4], [6–17]. Further, the shape of the distribution was taken to be circular in those studies, a model that is applicable only to a stationary source whereas it is double ellipsoidal or at most can be considered to be double elliptical for moving source as reported previously [5]. Further, in those studies, the voltage-current (V-I) characteristics of the power source, the process variables and the distribution parameters are not explicitly correlated and therefore its general use in the heat transfer model is limited.

In order to overcome the shortcomings of the previous studies, a fully developed parametric model explicitly relating the distribution parameter and process variables is developed in this study. The model is expressed as below:

$$a_f = c_1.U + c_2.I + c_3.D + c_4. \phi$$

(3)
\[ a = c_1.U + c_2.I + c_3.D + c_4. \phi \]  
\[ b = c_1.U + c_2.I + c_3.D + c_4. \phi \]  
where \( c_1, c_2, c_3 \) and \( c_4 \): regression coefficients, \( U \): speed, \( I \): current, \( D \): electrode distance and \( \phi \): electrode angle. The area of heat incidence, \( A_i \), was calculated using the Equations 3, 4 & 5 as expressed below:
\[ A_i = \frac{\pi}{2} (a_f b + a_r b) \]  

### 4.3 Determination of the Thermal Efficiency of the Arc

Thermal efficiency, \( \eta \), is defined as the ratio of the net heat reaching the surface of the substrate to the total heat generated and is expressed as:
\[ \eta = \frac{Q_{net}}{VI} \]  
where, \( Q_{net} \): heat (Watt) reaching the substrate surface, \( VI \): heat generated (Watt) where \( V \) (Volt) and \( I \) (Amp) are the voltage and the current. \( \eta \) can be readily evaluated if \( Q_{net} \) is known. Several studies have been conducted to determine the net heat flux and those methods are found to be cumbersome and have several drawbacks including (i) their inability to account for the heat loss during the transfer of the substrate and to differentiate between transient and quasi-stationary energies in the case of the calorimetric technique, (ii) the inaccuracy in the temperature measurement due to the presence of arc voltage during the process as the value is required in the inverse techniques such as genetic algorithm and simulated annealing methods [4], [6–13], [15–18]. It has been further observed that the results of various studies reported in the literature differ from each other in this regard and lack a feature directly relating the model parameters to the process variables. In lieu of these considerations, a simple and straightforward method to estimate the net heat flux would be highly appropriate and it becomes a necessity for solving the heat transfer equation.

#### 4.3.1 Parametric Model

In this work, a parametric model of the type expressed as below is constructed by using the data obtained from the procedure given below.
\[ \eta = c_1.U + c_2.I + c_3.D + c_4. \phi \]  

#### 4.3.2 Thermal Efficiency

The heat distribution on the substrate expressed in Equation 2 can be re-written in another form relating the peak intensity, \( Q_p \), and \( q(x,y) \) as below:
\[ q(x, y) = Q_p.e^{-\frac{3x^2}{a^2}}.e^{-\frac{3y^2}{b^2}} \]  
where \( Q_p = \frac{3\eta VI}{A_i} \)
Therefore, \( \eta = \frac{Q_p A_t}{3Vt} \) \hspace{1cm} (10)

It is to be noted that \( Q_p \) is the only unknown parameter. If \( Q_p \) is known, then the efficiency can be calculated from Equation 10.

4.3.3 Methodology

The methodology is to invoke an inverse technique, a combination of simulation and experimentation, to obtain a value for \( Q_p \) as described below,

1. By assuming an initial value for \( Q_p \), which is the heat source term of the model, Equation 1 is solved with appropriate initial and boundary conditions.
2. A temperature profile is obtained as illustrated in Figure 2a.
3. The width of the molten zone (modified layer) is obtained by knowing the demarcation boundary between the solidus and the liquidus temperatures of the substrate alloy.
4. Now, the simulated value for the width is compared with the experimental data (refer to Figure 2b for a macro-image of the modified layer).
5. If there is match between the two, then the assumed \( Q_p \) is correct; otherwise, re-run the simulation with another value for \( Q_p \).
6. This whole procedure is repeated for various process settings: current, speed, angle and electrode distance.

**Figure 2.** Simulated (a) and experimental (b) widths

5. MASS TRANSFER MODELLING

During the application of the heat on the substrate, the melting of the solute and the top surface of the substrate takes place. As a consequence, the solute is distributed into the molten zone due to convection and diffusion. Many of the earlier works concentrate on the heat and fluid flow, and had not been concerned with the solute distribution. Recently, a few investigations has been reported in the case of mass transfer occurring during surface alloying [19–21] and dissimilar welding [22–24] where a laser beam was used as the heat source. These studies have brought an insight to the solute distribution occurring in the SAP. Since
the GTA is an industrially important heat source, it is worthwhile to investigate the mass transfer modelling aspect for the development of surface-modified Bronze via the SAP with the GTA heat source as no research has been reported previously. Further, the above studies have invoked a complex model for the mass transfer to include the contribution by convection. The effect of convection can be rather easily handled by using an enhanced mass diffusivity as a single term in the equation. Recently, Chakraborty and Chakraborty [24] have shown that a diffusion coefficient, called, ‘eddy mass diffusivity’ was appropriate to account for the convection effect in the liquid zone. In this study, the model of Chakraborty and Chakraborty [24] is followed.

5.1 Governing Equation
A simplified governing equation applicable to the solute distribution in the SAP is expressed as: [3]

\[ \rho \frac{\partial c}{\partial t} = \rho \frac{\partial}{\partial x_i} \left( D \frac{\partial c}{\partial x_i} \right) + \rho U \frac{\partial c}{\partial x_1} \]  

(11)

where- \( D \): molecular and eddy mass diffusivities for solid and liquid zones, respectively and \( C \): concentration.

The above equation can be readily solved to obtain a concentration profile of the alloying element, in this case Ni, with appropriate initial and boundary conditions, provided the boundary between the melt and the un-melt zones are known. The thermal history obtained from the solution of the heat transfer equation provides the necessary information to identify the boundary between the melt zone and the un-melt zone.

6. EXPERIMENTAL WORK

The experimental work was divided into three parts to determine i) distribution parameters, ii) thermal efficiency of the heat source, iii) the melting and recrystallization of Ni in SAP.

6.1 Set-up
The set-up for all these experiments consists of a (i) Lincoln Electric V205T TIG welding machine at DCEN mode, (ii) manipulator with a working table driven by a servo-motor with a PLC controller, and (iii) imaging system with Dalsa vision appliance, a CCD grey-scale camera and Sherlock machine-vision software. The voltage was measured with a volt-meter. Argon was used as the shielding gas at 18 lpm flow rate. A 2.2% thoriated tungsten rod of 2.0 mm diameter, was used as the electrode.
6.2 General Procedure
The substrate was mounted on the working table, and held stationary or moved at a specified speed as per the requirement. The torch and the camera were held stationary.

6.3 Arc Parameters
Steel plates were used as the substrate material for these experiments. It was carried out for various settings of the process variables: current, speed, angle and electrode distance. Images of the arc were captured using the vision system during the progress of the experiments. The arc parameters were obtained from these images by employing an edge detection method.

6.4 Measurement of width for the evaluation of efficiency
The experiments were carried out for various settings of the process variables: current, speed, angle and electrode distance, using also the steel plates as the substrate. The widths and the depth of the bead (melted & re-crystallized zone) were measured by using a ruled grating.

6.5 Melting, mixing and recrystallization
These experiments were also carried out for various (i) settings of current, speed, and (ii) coating thicknesses, however, using Bronze or Cast Iron plates as the substrate. The concentration profiles, in this case Ni or Cr, were determined by using the EDAX spectrometry. Further, the hardness measurements were performed along the depth, width and longitudinal directions of the modified layer (melt-zone) by using Vickers micro-hardness tester. The modified layer width and depth were measured using a ruled grating.

7. SUMMARY AND CONCLUSION

7.1 Distribution Parameters
A parametric model between the arc parameters as a measure of the distribution parameters and the process variables constructed by a regression analysis using the experimental data is reported as below:

\[ a_f = 2.31 + 1.16 I_n - 0.21 U_n - 0.89 \Phi_n + 0.67 D_n \]  \hspace{1cm} (12)
\[ a_r = 2.06 + 1.35 I_n + 0.62 U_n - 0.39 \Phi_n + 1.04 D_n \]  \hspace{1cm} (13)
\[ b = 2.31 + 1.16 I_n - 0.21 U_n - 0.89 \Phi_n + 0.67 D_n \]  \hspace{1cm} (14)

where, \( I_n, U_n, \Phi_n \) and \( D_n \): the normalized values of the current, speed, electrode tip angle and electrode distance, respectively.

Based on the regression equations, it can be concluded that (i) the value of \( a_f \) increases with current and distance while it decreases with speed and angle, (ii) the value of \( a_r \) increases with current, speed and distance while it decreases with angle, (iii) the values of \( a_r \) and \( b \) are the
same indicating that the shape of the projected area of the arc (area of incidence) is not double elliptical as proposed by [5], rather it is semi-circular in the leading edge (front side) and is semi-elliptical in the trailing edge (rear side), and (iv) the effect of current is the most significant whereas the effect of speed is the least.

7.2 Thermal Efficiency

The regression analysis of the data relating the thermal efficiency with the process variables indicates that the thermal efficiency is nearly independent of current, speed, angle and distance and it remains constant around 74% as opposed to a range of 40-80% quoted in the literature for a GTA heat source.

7.3 Concentration profiles

Figures 3 shows the experimental data and the predicted values for the variation of the Ni concentration in the modified layer in the cases of Bronze and a similar trends was observed in Cast Iron substrates also. The experimental and the predicted Ni concentrations decrease with the distance (depth direction), showing a well-recognizable gradient.

The prediction of the trend is excellent whereas the computed values are in reasonable agreement with the experimental data in both cases. In the width direction, the variation of the Ni concentration for the Bronze case with distance is marginal, thus lacking a gradient. However, the predicted values reasonably agree with the experimental data.

![Figure 3a. Variation of concentration along the depth in the case of Bronze substrate](image)

![Figure 3b. Variation of concentration along the half-width in the case of Bronze substrate](image)

7.4 Effect of coating thickness

In order to assess the response of the model to the variation of the coating thickness, the computations were carried out assuming two thicknesses, 20 and 100 microns, and the computed values are plotted along with the 50 µm values as shown in Figure 4. The curve for 100 micron falls above and the one for 20 micron falls below the 50 µm curve. It is to be noted that Ni is introduced into the melt in the case of 100 micron is higher than that in the
case of 20 micron. This behaviour shows that the model responds well to the variation of the coating thickness and the prediction can be considered to be reliable.

![Graph showing Ni concentration against distance for various coating thicknesses](image)

**Figure 4.** Variation of the Ni concentration against distance for various coating thicknesses

7.5 Comparison - previous works vs. present study

The heat transfer models cited in the literature, in general, use the continuity and the momentum equations to obtain the convection in the liquid. Following the works of Zhang et al. [2], we have used an enhanced thermal conductivity to reflect the effect of convection and have predicted the melt-zone geometry, width and depth, that shows an excellent agreement with the experimental data. Similarly, using the eddy mass diffusivity proposed by Chakraborty and Chakraborty [24], we were able to compute the concentration profiles that reasonably in agreement with the experimental data. In the context of these findings, we propose that simplified heat and mass transfer models all that are required in the estimation of the solute distribution occurring in the SAP.

7.6 Hardness

The surface hardness was found to increase with increase in the Ni concentration as shown in Figure 5. Based on the observation, it may be concluded that the method of this study is capable of controlling the Ni content and the surface hardness, so as to obtain desirable tribological properties.
8. SCOPE FOR FUTURE WORK

This study can be further extended as given below:

i) A spinodal hardening treatment may be given to the surface-modified Bronze with Ni in order to further improve its hardness;

ii) The SAP may be developed for Brass to increase its wear resistance;

iii) Surface alloying/modification can also be carried out with the addition of non-metallic particulates such as SiC, Al₂O₃ to assess the improvement in wear properties of Bronze and Brass;

iv) A study on the improvement of the corrosion property of Bronze as well Brass may be highly complementary to the present work.

9. REFERENCES


23. N. Chakraborty, *The effects of turbulence on molten pool transport during melting and solidification processes in continuous conduction mode laser welding of copper –


10. PROPOSED CONTENT OF THE THESIS

Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: Heat Transfer Modelling of SAP
Chapter 4: Heat Source Modelling
Chapter 5: Determination of Thermal Efficiency
Chapter 6: Mass Transfer Modelling of SAP
Chapter 7: Experiments
Chapter 8: Results and Discussions
Chapter 9: Conclusions
Chapter 10: Future Directions
References

11. PUBLICATIONS BASED ON THE RESEARCH WORKS

International Journal