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Quantification of the heat transfer during the plasma arc re-melting of titanium alloys

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ABSTRACT

This paper summarizes the development and application of an Inverse Heat Conduction Code (IHCC) to determine the surface heat flux distribution from an industrial plasma torch applied to heat a sample of Ti-6wt%Al-4wt%V (Ti64) alloy. The test (trial) was conducted within an industrial scale plasma arc furnace and the sample was instrumented with 15 thermocouples embedded below the top surface. The sample was heated for 278 s, which allowed sufficient time for a liquid pool to form within the sample. Following the trial, the sample was sectioned to obtain the liquid pool profile. The IHCC analysis method described in the paper is based on the future time-step approach and uses the commercial finite element code ABAQUS™ as the forward conduction engine. The IHCC analysis was conducted with both isotropic thermal conductivity and anisotropic thermal conductive in the liquid. The later, was used to approximate the effect of fluid flow on heat transport in the liquid. Additionally, the method used linear interpolation to vary the estimated heat flux between the discrete heat flux evaluation points associated with the thermocouple positions. The results indicated that it is critical to account for fluid flow and suggest that the heat flux distribution can be accurately described by two over-lapping Gaussian distributions: one narrow distribution associated with convective heat transfer; and a second, broader distribution, associated with radiation. An overall heat transfer efficiency of 28% was estimated from the heat flux distribution.

1. Introduction

Titanium alloys are used extensively in the aerospace sector for aero-engine and airframe components due to their relatively high strength and low density [1]. The need to consolidate both primary titanium sponge and revert material into primary ingot, and to ensure the elimination of feedstock related defects, has resulted in the development of a number of sophisticated melt-consolidation technologies including the Electron Beam Cold Hearth Re-melting (EBCHR) process and the Plasma Arc Cold Hearth Re-melting (PAM) process. These technologies, often referred to as Cold Hearth Melting (CHM) technologies, exploit density separation and extended liquid metal residence times to facilitate liquid metal refining [2].

The EBCHR process accounts for the largest percentage of commercial CHM production. There are a number of commercial EBCHR furnaces that have been qualified as part of the process route for the production of premium quality, or rotor grade titanium – for example EBCHR followed by Vacuum Arc Remelting (VAR). The EBCHR is utilized for its ability to gravity separate High Density Inclusions (HDI's) and it relatively long liquid metal residence time for removal of High Interstitial Inclusions (HID's) [2]. The disadvantage of the EBCHR process is that the vacuum environment needed to enable the generation and transmission of the electron beam results in high evaporation rates of the more volatile alloy constituents, such as Al and Cr.

In the PAM process, an inert gas environment (Ar or He) is typically used to avoid oxidation and nitrogen pick-up and to also generate the plasma used to provide the process heat. The commercial processes typically use inert gas pressures at or slightly below atmospheric pressure, which significantly reduces the evaporation rate of alloying elements. Thus, for alloys containing concentrations of elements with high vapor pressures, the PAM process has a distinct advantage over EBCHR.

There have been a limited number of studies of the PAM process. Ward et al. [3] investigated the relationship between the casting conditions and pool shape in a plasma arc ingot casting process

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for a nickel-based superalloy. Huang et al. [4] investigated the behavior of inclusions in the refining hearth of a PAM furnace. Huang's model assumed that the heat flux from the plasma torch exhibits a Gaussian distribution. The effects of gas shear stress, electromagnetic forces and Joule heating were incorporated. The predicted pool shape and inclusion trajectories agreed well with the experimental measurement. Li [5] developed a model for the reversed-polarity plasma torch in the titanium hearth melting process. The model calculates the heat flux, current density and surface shear distribution at the plasma/melt interface. The predicted heat flux distribution shows a maximum heat flux away from the axial center instead of a Gaussian distribution. Based on the predictions, in a separate study, Huang [6] performed a sensitivity analysis on the effects of process parameters on the liquid pool depth. Results showed that, the torch power, Marangoni forces and heat transfer coefficient play important roles. The emissivity of the top surface was shown to affect a small portion of heat flux near the top surface where the temperature is high. Lothian et al. [7] developed a numerical model of the remelting process for a nickel-based superalloy disk to investigate heat transfer, buoyancy, fluid flow and electromagnetic effects. The torch was held stationary above the center of the pool and the heat flux applied in the model was a Gaussian distribution. Their results showed that the average Lorentz force is in general much smaller than buoyancy. The sensitivity analysis indicated that torch power and surface tension gradient are the main parameters that dominate the shape of the pool.

The literature reviewed to date predominantly assumes that the heat flux from the plasma torch may be described as having a Gaussian distribution. In this work, an Inverse Heat Conduction Code (IHCC) was used to estimate the heat flux distribution based on a set of temperatures measured in a disk of titanium within a commercial plasma furnace. The focus of the work is to better understand the heat transfer (quantity and distribution of heat) from a plasma torch to titanium under typical conditions existing in a commercial PAM process. This understanding is critical to fully exploit the advantages of this technology and to improve the industrial-scale process.

2. Experimental method

The instrumented thermocouple trial was conducted in an industrial scale plasma arc furnace located at a commercial facility. The trial involved measuring the evolution in temperature in a cylindrical block during heating with a stationary plasma torch. For the trial, the power of the plasma torch was set at 300 kW – current 1000 A, voltage 300 V – which was used to heat the block for 278 seconds. The torch used helium and an average pressure of the chamber was 425 Torr (0.56 atm). The torch standoff distance was 0.3048 m (12 in).

2.1. Test block

A cylindrical sample of Ti-6wt%Al-4wt% V (Ti64), 0.4191 m (16.5 in) in diameter and 0.0762 m (3 in) thick was used to conduct the test (the "test block"). The test block was placed on top of the starter block in the mould of the plasma furnace. Several copper spacers were placed under the test block to raise it to ensure that the surface of the test block was at a height consistent with the metal surface during casting operations and to provide space to run thermocouple wires out from under the test block. The plasma torch was located directly above the top surface of the block. Fig. 1 shows a photo of the test block and its setup in the mould cavity.

Fig. 1. Test block sitting at the top of the mould in the plasma arc furnace.

2.2. Thermocouple positions

The test block was instrumented with 15 K-type thermocouples. The thermocouples were installed in holes that were 0.0127 m (0.5 in) deep and were drilled from the bottom surface of the test block. Thus, the thermocouple tips were 0.0635 m (2.5 in) below the top surface of the test block. This distance was chosen so as to avoid the thermocouples contacting molten titanium, which would cause Type-K thermocouples to fail within a short timeframe.

The thermocouples were positioned along two lines oriented 90° from each other as shown in Fig. 2. This layout was designed to assess the symmetry of temperature distribution in the block.

3. Inverse heat conduction model development

The inverse heat conduction code (IHCC) was developed in Python, using the commercial finite element software ABAQUS™ (v16.4) as the forward conduction model, which is a commercial finite element analysis package.

3.1. Forward heat conduction model

The forward heat conduction model is used to calculate the transient temperature response of the test block. The governing heat conduction equation that is solved in this model is:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + Q \tag{1}$$

where ρ is the density (kg/m^3), c_p is the specific heat capacity (J/kg·K), k is the thermal conductivity (W/m·K), T is the temperature (K), and Q is a heat source associated with the latent heat of phase transformations (W/m^3).

Fig. 3 shows the domain of the model. By assuming axisymmetric conditions exist, the test block can be represented by a rectangular domain with an area of 0.0762 m × 0.21 m (8.25 in × 3 in). The rotational axis (r = 0) is aligned with line AB as shown in Fig. 3. A uniform element edge length of 4 mm has been used and the total number of nodes and elements is 3166 and 1007, respectively.

3.2. Boundary conditions

3.2.1. Top surface

The boundary condition applied to the top surface includes heat input from the plasma torch and heat losses due to radiation and convection. The expression representing the net heat flux to the top is: