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Experimental Observation and Analytical Modeling of Melting and Solidification during Aluminum Alloy Repair by Turbulence Flow Casting

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***Abstract* – This paper presents an overview on the state of the art of applicable casting technology for applications in the field of repairing Aluminium Alloy components. Repair process on the Aluminium sample using similar metal has been carried out to investigate the micro-structural effect. Joining occurs as a result of convection heat transfer of molten flow into the sand mold which melts the existing base metal inside the mold and subsequent solidification. The analytical model has been developed to describe aluminium component repair by Turbulence Flow Casting. The model built is based on heat transfer principle that can handle the phenomena of heat flow. The experimental result and analytical model analyses pointed out that joint quality are greatly affected by parameters of *preheating temperature* and *duration of molten metal flow* in the mold. To obtain a desired metallurgical sound at the joint, the optimum temperature and time were adjusted in order to obtain a similarity of microstructure between filler and base metal. This model is aimed to predict the use of the process parameter ranges in order to have the optimum parameters when it is applied to the experiment. The fixed parameters are flow rate, sand ratio, and pouring temperature. The process parameters are preheating temperature and pouring time. It is concluded that anaytical modeling has good agreement with the experimental result.**

***Index Terms* — Repair, Turbulence Flow Casting, Aluminium alloy, preheating temperature, pouring time, analytical model.**

I. INTRODUCTION

Problems involving the solidification and melting of materials frequently arise in industrial processes such as casting, welding, spray coating, thermal energy storage, etc [1]. In this work, melting and solidification phenomena are observed during Aluminium alloy repair of Al-12%Si by the Turbulence Flow Casting. This process is a new developed method in our present work used to repair the cracks or some other defects on this material instead of using conventional processes such as TIG and MIG. Knowing so far that joining Aluminum alloy has a problem with Aluminum oxide which melts at about 2050^{o}C and it is much higher than the melting point of the base metal. If the oxide is not removed or displaced, the result is incomplete fusion. Furthermore, hydrogen dissolves very rapidly in molten aluminum and it has been determined to be the primary cause of porosity in aluminum welds. High temperatures of the weld pool alloy a large amount of hydrogen to be absorbed, and as the pool solidifies, the solubility of hydrogen is greatly reduced. Hydrogen that exceeds the effective solubility limit forms gas porosity unless it escapes from the solidifying weld.

The overview above indicates that it is required to build a new method for aluminum alloy components. Basically, joining process in Turbulence Flow Casting is similar with casting process, but the difference is molten metal let flows out of the mold. Joining occurs as a result of convection heat transfer of molten metal flow into the sand mold which contacts and melts the existing component defect inside the mold and subsequent solidification. The molten filler metal and the base metal at the surface defect will then mix together as a unity when freezing. Therefore, two main phenomena of this process are melting and solidification.

According to some literatures that the analytic solution of this problem, however, is extremely difficult due to the existence of a moving boundary resulting from phase change. Thus, another difficulty is also the governing equation is a partial differential equation for which the particular solutions are unknown when physically realistic boundary conditions are imposed. Analytical solutions are possible only for a few special classes of boundary and initial conditions, for example, Stefan or Neumann's problems [12]. For other more complicated boundary conditions, different assumptions have to be used. Series solutions have been attempted. More recently, Foss [12] presented a simple approximate solution to an important class of moving boundary problems; the freezing and melting of lake ice. A convective boundary was applied to the air-ice interface. The solution compared closely with Westphal's more accurate series solution. However, the initial water temperature in both cases was assumed to be at the fusion temperature, thus, ignoring conduction in the liquid phase. This limits the usefulness of the solutions in many practical applications. This paper presents an approximate analytical solution to the moving boundary problem associated

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with the solidification and melting. The equation built in this work is deduced from the differential equations describing the phenomenon to collect proper selection of variables and finally to make dimensionless parameters. The aid of these equations is formulated from a boundary-value problem in which the governing equation is the general conduction equation for the solid phase. Then, the dimensionless equation is combined with the experimental data to obtain the empirical equation describing the solidification and melting process involved in this experiment. So, the objectives of the present work are (i) to develop analytical model of melting and solidification related to the experimental repair process and (ii) to build the empirical equation correlating the dimensionless equation with the experimental data. Therefore this empirical equation, as a generalized formulation, can be used to predict and select the process paremeters which was not performed in the previous experiment.

II. EXPERIMENTAL AND ANALYTICAL APPROACH

The material used for the experiment was Aluminum alloy Al-12%Si. Repair process with the similar alloy is performed to the specimen 100 x 25 x 15 mm containing defect of 10 x 10 x 15 mm at the middle position.

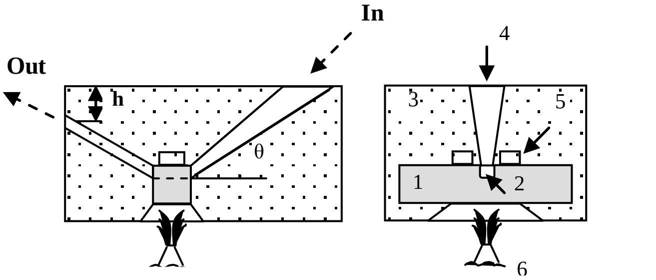

Figure 1: Schematic representation of 2D Physical model of turbulence flow casting process.

Joining occurs by convection heat transfer of molten flow into the sand mold which contacts and melts the existing component inside the mold and subsequent solidification. Fixed parameters are flow rate 1.0 - 1.2 kg/s, pouring temperature 720-780°C, preheating temperature 200 °C. (see figure 1).

A. Analytical Approach for Melting Phenomenon

Figure 2 shows the temperature distribution in an metal layer on the surface of a liquid. The upper face is exposed to air at room temperature. Solid formation occurs progressively at the solid-liquid interface as a result of heat transfer through the solid phase to the air. Heat flows by convection from the liquid to the solid region, by conduction through the solid, and by convection to the sink. The solid layer is cooled except for the interface in contact with the liquid, which is at the freezing point. A portion of the heat transferred to the sink is used to cool the liquid at the interface *SL* to the freezing point and to remove its latent heat of solidification. The other portion serves to cool the solid phase.

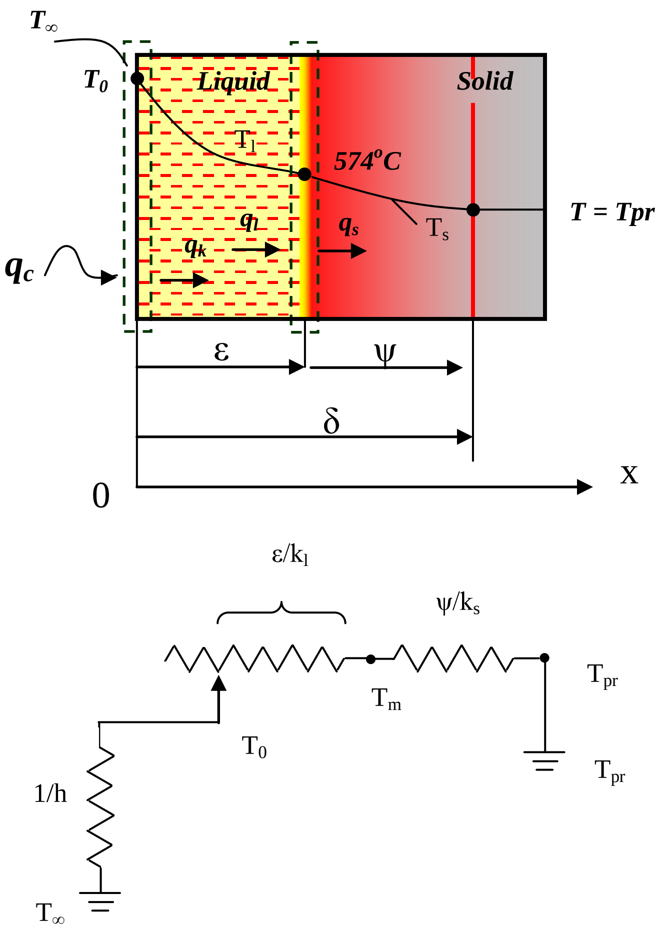

Figure 2: Temperature distribution and simplified thermal circuit for melting phenomenon.

The solidification or melting of a metal can be formulated as a boundary-value problem in which the governing equation is the general conduction equation for the solid, is

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Subject to the boundary conditions that

$$-k\frac{\partial T}{\partial x} = \bar{h}_0 (T_{x=0} - T_\infty) \qquad \text{at } x = 0$$

$$k\frac{\partial T}{\partial x} = \rho L_f \frac{d\varepsilon}{dt} + \bar{h}_\varepsilon (T_l - T_{fr}) \qquad \text{at } x = \varepsilon$$

where:

ε	=	distance to the solid-liquid interface, which is a function of time *t*
L_f	=	latent heat of fusion of the material
α	=	thermal diffusivity of the solid phase ($k/\rho c$)
ρ	=	density of the solid phase
T_l	=	temperature of the liquid
T_∞	=	temperature of the heat sink
T_{fr}	=	freezing-point temperature

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h_0	=	coefficient at x = 0, the air-solid interface
h_ε	=	coefficients at $x = \varepsilon$, the liquid-solid interface

The analytic solution of this problem is extremely difficult and has been obtained only for special cases. To simplify the analysis further, it is assumed that the physical properties of the the metal ρ, k, and c, are uniform, that the liquid is at the solidification or melting temperature (i.e., $T_l = T_{fr}$ and $1/h_\varepsilon$ = 0), and that h_0 and T_∞ are constant during the process. Moreover, the solution will be in dimensionless parameters through the fundamentals principle of heat transfer that the rate of heat flow per unit area through the resistance offered by the metal and the air, acting in series, as a result of the temperature potential (T_{fr} - T_∞) *is*

$$\frac{T_\infty - T_0}{1/h} + \frac{T_0 - T_{pr}}{\varepsilon/k + \psi/k} \qquad \text{....... (1)}$$

This is the heat flow rate that removes the latent heat of fusion necessary for freezing at the surface $x = \varepsilon$ and the energy required to change the solid phase to liquid and to increase the temperature in SL region, that is

$$\rho\left[L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right]\frac{d(\varepsilon+\psi)}{dt} \qquad \text{....... (2)}$$

Where is the volume rate of solid formation per unit area at the growing surface (m3/hr m2) and Lf is the latent heat per unit volume (J/m3). Combining Eqs. (1) and (2) to eliminate the rate of heat flow yields

$$\frac{T_\infty - T_0}{1/h} + \frac{T_0 - T_{pr}}{\varepsilon/k + \psi/k} = \rho\left[L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right]\frac{d(\varepsilon+\psi)}{dt} \qquad \text{....... (3)}$$

To make this equation dimensionless let

$$x^* = \frac{h(\varepsilon+\psi)}{k} \qquad dx^* = \frac{h\,d(\varepsilon+\psi)}{k} \qquad T^* = \frac{(T_\infty - T_0)}{(T_0 - T_{pr})}$$

and

$$t^* = \frac{h^2(T_0 - T_{pr})t}{\rho k\left[L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right]}$$

So, the dimensionless equation is

$$dt^* = \frac{x^*}{T^* x^* + 1}dx^* \qquad \text{....... (4)}$$

If the melting process starts at t = t = 0 and continuous for a time t and ε = 0 → $x^* = h\psi/k$, the solution of Eq. (4), obtained by integration the specific limits, is

$$\int_0^{t^*} dt^* = \int_{\frac{h\psi}{k}}^{x^*} \frac{x^*}{(1 + T^* x^*)}dx^* \qquad \text{....... (5)}$$

The dimensionless equation corresponding to Eq. (5) in the foregoing simplified treatment becomes

$$t^* = \frac{x^* + 1}{T^*} - \frac{1}{(T^*)^2}\left[1 + \ln\left(\frac{1 + T^* x^*}{2 - T^*}\right)\right] \qquad \text{....... (6)}$$

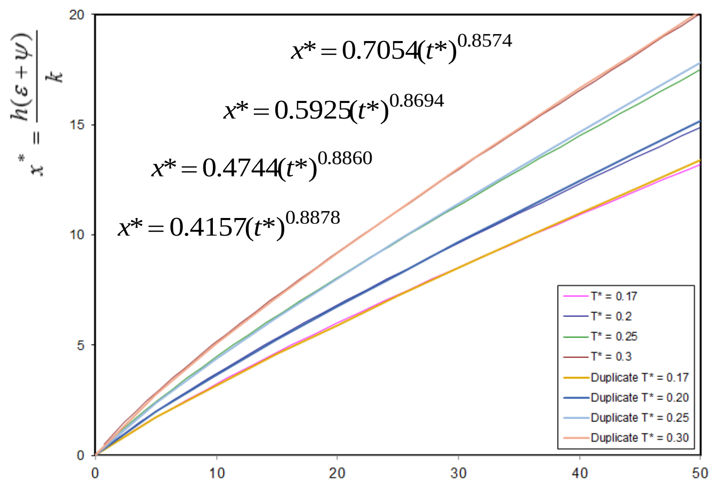
The correlation of dimensionless parameters actually required in the above equation is in the form of $x^* = f(t^*, T^*)$. To modify this equation is quite complicated so that it is calculated and plotted in the form of curve between x^* versus t^* as seen in figure 3. From this curve, it can be obtained an approximate dimensionless equation, that is

$$x^* = A(t^*)^B \qquad \text{....... (7)}$$

where:

$$A = 2.1813(T^*)^{0.9404} \qquad \text{........ (8)}$$

$$B = -0.2492(T^*) + 0.9325 \qquad \text{........ (9)}$$



$$t^* = \frac{h^2(T_0 - T_{pr})t}{\rho k\left[L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right]}$$

Figure 3: Total heat penetration depth or generalized thickness against generalized time from Eq. 6 for various generalized temperature.

The physical properties of Al-12%Si at 20°C are density 2659 kg/m^3, heat capacity C_p = 871 J/kg K, thermal conductivity k = 164 W/m K, thermal diffusivity α = 7.1 x 105 m^2/s, and latent heat of fusion is 398 kJ/kg. Thus, we take an experiment with temperatures of pouring temperature (T_∞), preheat temperature (T_{pr}), freezing temperature (T_{fr}), and

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average temperature (T_0) between T_∞ and T_{fr} respectively are 780°C, 200°C, 574°C, and 677°C. Finally, it is plotted the calculated data obtained from the analytical solution previously described to compare with the experimental result, that is

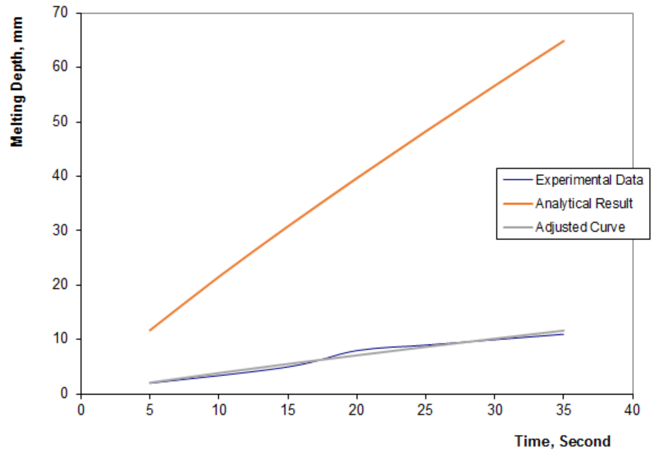

Figure 4: Comparison melting depth versus time resulted from the experiment, analytical calculation (Eq. 7) and adjusted curve from the both results.

From figure 4, the adjusted factor for analytical equation can be determined about 0.18. From this result, finally Eq. 7 becomes

$$x^* = 0.18A(t^*)^B$$

or

$$x = \frac{0.18\,kA}{h}\left(\frac{h^2\left(T_0 - T_{pr}\right)t}{\rho k\left[L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right]}\right)^B$$

which describes the melting depth for liquid region.

B. Analytical Approach for Solidification Phenomenon

The schematic of solidification phenomenon is depicted in figure 5. The energy balance at S/L interface:

$$\left[k_s\frac{\partial T_s}{\partial x} - k_l\frac{\partial T_l}{\partial x}\right]_{x=\varepsilon(t)} = \rho\left[L + C_p(T_0 - T_m)\right]\frac{\partial\varepsilon(t)}{dt}$$

From the basic equation, temperature equation in liquid region is

$$T_l = T_0 - \frac{h\varepsilon}{k_l}(T_\infty - T_0)\left(\frac{x}{\varepsilon}\right) + \left[-(T_0 - T_m) + \frac{h\varepsilon}{k_l}(T_\infty - T_0)\right]\left(\frac{x}{\varepsilon}\right)^2$$

And, temperature equation in solid region is

$$T_s = T_m - 2(T_m - T_{pr})\left(\frac{x-\varepsilon}{\delta-\varepsilon}\right) + (T_m - T_{pr})\left(\frac{x-\varepsilon}{\delta-\varepsilon}\right)^2$$

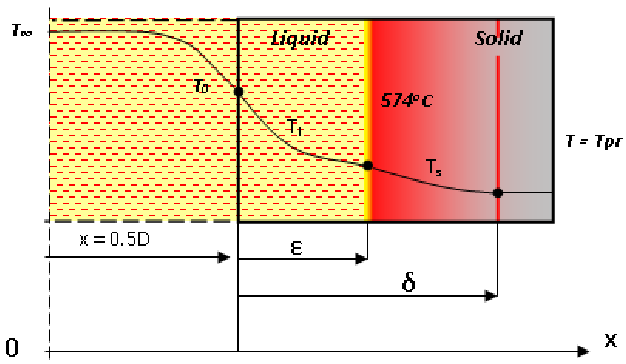

Figure 5: Temperature distribution for solidification phenomenon.

the equation for liquid region against x at x = ε, is

$$\left.\frac{dT_l}{dx}\right|_{x=\varepsilon} = \frac{h}{k_l}(T_\infty - T_0) - \frac{2}{\varepsilon}(T_0 - T_m)$$

and, the equation for solid region against x at x = ε, is

$$\left.\frac{dT_s}{dx}\right|_{x=\varepsilon} = \frac{-2(T_m - T_{pr})}{\delta - \varepsilon}$$

If $k_s = k_l$, and heat flux at *S/L interface* is constant then

$$k_s\left[\frac{-2(T_m - T_{pr})}{\delta-\varepsilon}\right] - k_l\left[\frac{h}{k_l}(T_\infty - T_0) - \frac{2}{\varepsilon}(T_0 - T_m)\right] = \rho\left[L + C_p(T_0 - T_m)\right]\frac{\partial\varepsilon(t)}{dt}$$

$$\left[\frac{2(T_m - T_{pr})}{\delta-\varepsilon}\right] - \left[\frac{h}{k_l}(T_\infty - T_0) - \frac{2}{\varepsilon}(T_0 - T_m)\right] = \frac{\rho\left[L + C_p(T_0 - T_m)\right]\varepsilon}{k(T_0 - T_m)}\frac{\partial\bar{T}}{dt}$$

Assume that solidification occurs at constant temperature (quasi-steady) so that, $\frac{d\bar{T}}{dt} = 0$ then

$$\varepsilon^* = \frac{3}{T^*} - 5$$

Substitute Eq. 11 to Eq. 12, so it becomes

$$0.18A(t^*)^B = \frac{3}{T^*} - 5$$

And finally, it is obtained

$$t^* = \left[\frac{16.7}{T^*A} - \frac{27.8}{A}\right]^{B^{-1}}$$

In the same way as described in Eq. 6, then the equation … becomes

$$T^* = 2.36\,(t^*)^{-0.46}$$

or

$$T^* = 2.36\left[\frac{h^2\left(T_0 - T_{pr}\right)t}{\rho k\left\{L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right\}}\right]^{-0.46}$$

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It has been performed a correction of the equation above by the experiment result which yields

$$T^* = 0.83\,(t^*)^{-0.35}$$

$$T^* = 0.83\left[\frac{h^2\left(T_0 - T_{pr}\right)t}{\rho k\left\{L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right\}}\right]^{-0.35}$$

The numerator and denominator at the right hand side of the equation above are divided by (T_∞ and T_0), so

$$T^* = 0.83\left[\frac{\dfrac{h^2\, t}{T^*}}{\rho k\left\{L + C_p(T_0 - T_m) + C_p(T_m - T_{pr})\right\}}\right]^{-0.35}$$

Take a definition for average C_p that $C_p = 0.5\,(C_{p1} + C_{p2})$

$$T^* = 0.83\left[\frac{\dfrac{h^2\, t}{T^*}}{\rho k\left\{\dfrac{L}{(T_\infty - T_0)} + \dfrac{\overline{C}_p}{T^*}\right\}}\right]^{-0.35}$$

$$T_0 = \frac{1}{2}(T_\infty - T_m),\ \ T_\infty - T_0 = T_0 - T_m,$$

$$\textit{then, } L = 2.5\overline{C}p\left(T_\infty - T_0\right) = \overline{C}p\left(T_0 - T_m\right)\textit{, so}$$

$$\tau = \left(2.5T^* + 1\right)\left(\frac{0.83}{T^*}\right)^{2.86} \qquad \ldots\ldots\ (10)$$

where

$$\tau = \frac{h^2\, t}{\rho k\overline{C}_p}$$

Simplify the equation (10) by plotting it in the form of curve correlation between T* and τ, which is

$$T^* = 1.23\,\tau^{-0.41} \qquad \ldots\ldots\ (11)$$

$$\frac{\left(T_m - T_{pr}\right)}{(T_\infty - T_m)} = -0.5 + 0.41\left(\frac{h^2\,\alpha t}{k^2}\right)^{0.41} \qquad \ldots\ldots\ (12)$$

Simplify again the equation (12) by plotting it in the form of curve correlation between θ and τ, then

$$\theta^* = 0.11\,\tau^{0.702} \qquad \ldots\ldots\ (13)$$

$$\frac{\left(T_m - T_{pr}\right)}{(T_\infty - T_m)} = 0.11\left(\frac{h^2\,\alpha t}{k^2}\right)^{0.702} \qquad \ldots\ldots\ (14)$$

Where

T_{pr} = preheating temperature
T_m = melting temperature
T_∞ = liquid temperature
k = thermal conductivity

Finally, we have the equation relating the preheating temperature and pouring time.

$$T_{pr} = T_m - 0.11(T_\infty - T_m)\left(\frac{h^2\,\alpha t}{k^2}\right)^{0.702} \qquad \ldots\ldots\ (15)$$

The Eq. 15 can be plotted in the form of curve as depicted in figure 6.

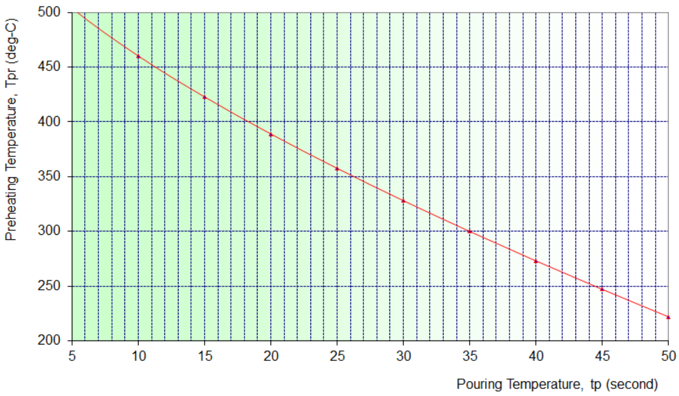

Figure 6: Preheating temperature versus pouring time curve plotted from Eq. 15.

III. RESULTS AND DISCUSSION

As stated in earlier above that the problem of heat conduction involving solidification and melting are complicated because the interface between the solid and liquid phases moves as the latent heat is absorbed or liberated at the interface. The location of the moving interface is not known a priori, and the thermal properties of solid and liquid are different. Therefore, the analytical modeling presented here is started from a collecting a various physical parameters involving the phenomena of solidification and melting using one-dimension basic heat transfer concept. Thus, these parameters was arranged to become the dimensionless parameters. Furthermore, the dimensionless parameters are arranged and combined with the experimental results to obtain the approximate analytical formulation. The result is presented in Eq. 15. Both of equation and curve can be used to select the preheating temperature and pouring time of molten metal inside the mold to obtain a practicable experiment result in accordance with expected joint. The parameters of preheating temperature and pouring time and melting depths resulted from the experiments and an analytical formulation agreed for practical purpose since the analytical equation built was combined with the experiment result.

IV. CONCLUSIONS

An Analytical modeling can be used for selecting some parameters of repair process by Turbulence Flow Casting method. The modeling of melting and solidification enables to obtain melting depths and correlation between preheating temperature and pouring time, so the data representing the experiment can be used. Moreover, it will enrich the whole experiment results and analysis, reduce cost and less time consuming.

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