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Experimental and Numerical Investigation of Melting and Solidification during Gray Cast Iron Repair by Turbulence Flow Casting

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Abstract: A two-dimensional numerical model has been developed to predict microstructure during gray cast iron repair by Turbulence Flow Casting method. The model built is based on fluid flow coupled heat transfer that can handle phenomena of melting and solidification. The experimental and numerical investigation pointed out that microstructure changes are greatly affected by parameters of *preheating temperature* and *duration of molten gray iron flow* in the mold. To obtain a desired metallurgical sound at the joint, the optimum temperature and time are adjusted respectively for 500-700^{0}C and 10-15s. It is concluded that numerical simulation has good agreement with the experimental results.

Keywords: Turbulence Flow Casting, gray cast iron, repair, melting, solidification, microstructure

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1 INTRODUCTION

Problems of melting and solidification 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 gray cast iron repair by the Turbulence Flow Casting method. This repair process is a new method developed in our present work used to repair the cracks or some other defects on components of gray cast iron so that the component is like new. It means that the continuity of materials properties at the area of joint after the repairing will back to the original characteristics. This method was developed to improve the quality of joint instead of general method i.e. arc-welding and oxyfuel gas welding [2]. As we know so far that the repair process of gray cast iron components by such conventional welding methods is problematic and difficult especially cracking occurs due to the brittleness [2-4]. These processes also require long exposure time at high temperature or high pressure, leading to graphite coarsening and high residual stress near joint [5]. Cracking in vicinity of joint occurs as a result of combination of contraction strain, white cast iron at fusion zone, and high carbon martensite in heat affected zone (HAZ) which is accompanied by micro-cracks (fissures) [6]. Some researchers [7-8] try to build another method such as diffusion welding by Ni-powder spray welding and solid-state welding by diffusion bonding performed at elevated temperatures and high contact pressure simultaneously. But, area of joints resulted from these methods is very low strength and containing porosities. The other methods which principally could be applied to repair gray cast iron components, from recent literatures, are ultrasonic insert casting [9], friction welding [10], and impact-electric current discharge joining [5]. However, they are not only difficult to apply in repairing component with complex shape and large dimensions but also they are practically inapplicable easily in the field.

The overview above indicates that it is required to build a new method for the repairing gray cast iron 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. These phenomena, then, are simulated by using Computational Fluid Dynamics (CFD) to predict the melting depth during fluid flow process and to predict the microstructure when the fluid reaches a freezing point. Fluid flow simulations in model describing such phase change problems are rarely found in the literature [11]. In fact, from realistic consideration, fluid flow model with conjugate heat transfer is needed to get accurate temperature distribution for subsequent solidification [12]. The reason why fluid flow rarely involved, researchers assume that simulating fluid flow is usually the most computationally expensive part and often

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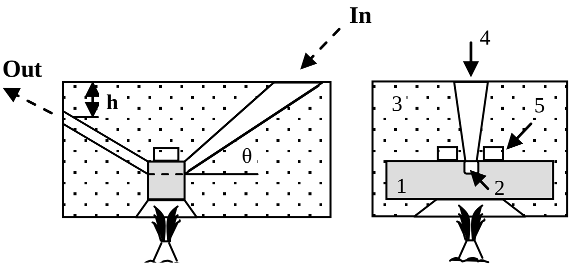
wonder if they should do it at all [13]. Chao and Du [14] ignored this fluid model since the temperature distribution in the sand mold during casting is of less interest and requires a great deal of computing effort so they approach the solution by equivalent heat transfer coefficient used for the sand mold. Regarding with this work, fluid flow should be considered as an essential part especially in predicting melting depth which is strongly needed when applied to the practical purpose. The objectives of the present work are (i) to develop numerical simulation of melting and solidification related to repair process, using finite element method and (ii) to validate the result of simulation by comparing with the experimental data. From these investigations, it is expected to get a relevant connection between both results so that the difficult parameter to apply in the experiment can easily be simulated by numerical approaches. Therefore, numerical simulation in terms of melting and solidification phenomena is special cases which should receive a fully attention in repair process by Turbulence Flow Casting method.

2 EXPERIMENTAL AND NUMERICAL APPROACH

The material used for the experiment was gray cast iron, with composition of 3.6 mass%C and 2 mass%Si, 0.6 mass%Mn, 0.06 mass%P, and 0.05 mass%S. Repairing with the similar alloy is performed to the specimen 150 x 25 x 25 mm containing defect of 20 x 20 x 20 mm at the middle position. 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, sand ratio 8 - 12, pouring temperature 1350-1380^{0}C, and inlet angle about 30^0 (see Figure 1).



Remarks: (1). Specimen, (2). Defect, (3). Sand mold, (4). Inlet/Outlet, (5) Heating coil, (6). Flame.

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

The process parameters are preheating temperature and pouring time. The preheating temperatures are applied and arranged starting from room temperature, 100, 200, 300, 400, 500, 600, and 700^{o}C. The pouring time was in the range 5 up to 30 for each 5 time interval.

Numerical simulation is computer-based computation using Computational Fluid Dynamics (CFD) and Thermal modules. The physical model in Figure 1 is taken to be a finite element model as represented in Figure 2. It can be seen from that figure that the element mesh is very fine, about 11,600 elements and 2.5 mm for each element length, aimed to increase computation accuracy. The time step for iterative process is calculated 0.25 s, for running execution time 20 s. The sequence of all simulation is described briefly: fluid flow model, at first running, having - *rtf* extension file, is used for heat transfer model as its initial condition to determine melting depth. Then, heat transfer model resulted from melting simulation, as -*rth* extension file, is to initiate the condition of solidification model. Finally, cooling curve resulted from the latest model representing the prediction of microstructure referred to the eutectic transformation of iron- carbide equilibrium phase diagram is obtained.

The thermophysical properties of green sand mold used in this simulation are thermal conductivity 0.52 W/m.K, specific heat 1170 J/kg.K, and density 1496 kg/m^3 [15]. Viscosity of molten gray cast iron for this simulation is 5.5 g/m.s. The thermophysical properties of gray cast iron used can be seen in Figures 3 and 4.

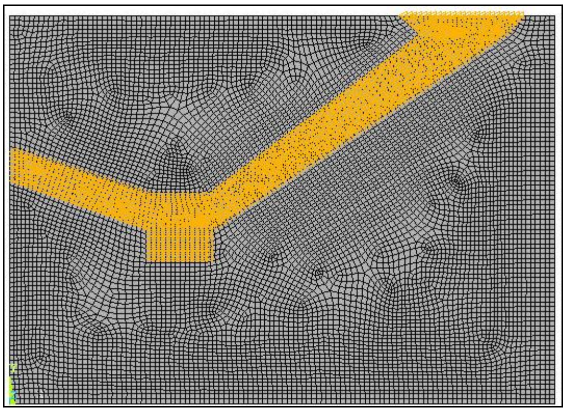


Figure 2: Finite element model for Flow-casting simulation

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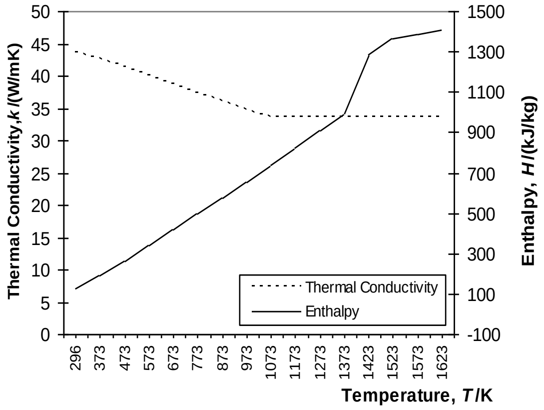


Figure 3: Thermal conductivity and enthalpy for gray cast iron used in melting and solidification models. [16-17]

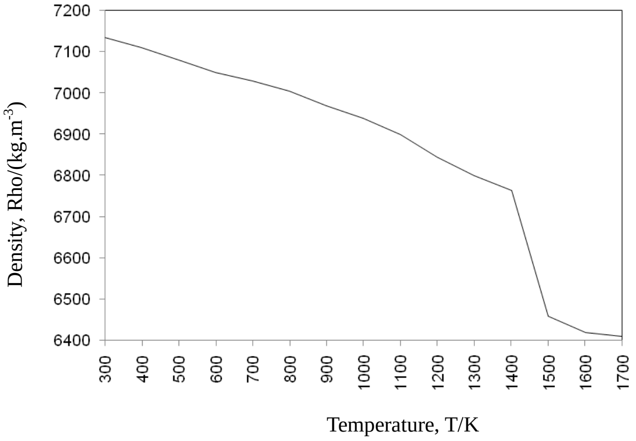


Figure 4: Density for gray cast iron used in melting and solidification models. [17].

RESULTS AND DISCUSSION

3.1 Experiments

Turbulence Flow Casting method, as a new solution, is powerful since joint area after repair process was free of cracks and brittleness. It was the cause of the process undergoing in sand mold where cooling rate can be minimized as low as possible, preventing the formation of undesirable white cast iron. The key is cooling rate. Moreover, the continuity and properties of material at the area of joint was back to the original characteristics prior to defect or failure. The example of its microstructure is depicted in fig. 5 for preheating temperature and pouring time of 650^{0}C and 15 s, respectively. It can be seen, the typical flake graphite cast iron structure in base metal and weld pool. On the other hand, it may find the white cast iron (see Figure 6) if selection of the parameters is improper.

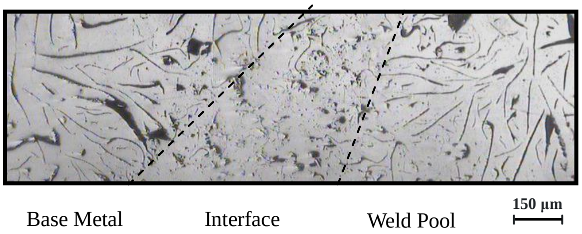


Figure 5: Photograph of microstructure after repair process, etched by nital 3%

For instance, we could be seen the microstructural evolution in area of weld pool after repair process where the parameters applied are preheating temperature of only 200^{0}C and pouring time of 20 s.

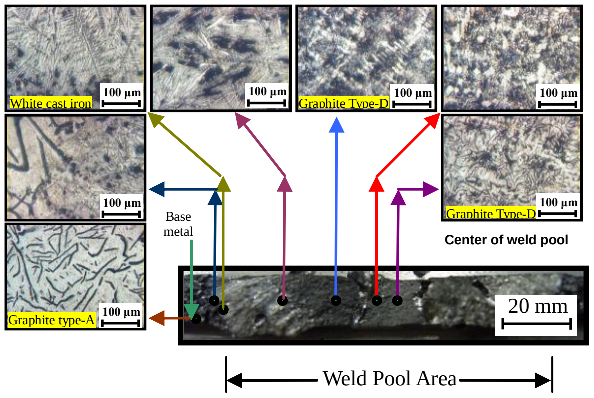


Figure 6: Microstructural evolution on the area of joint after repair, etched by nital 3%.

3.2 Numerical Simulations

The exciting point that could be highlighted from this work, that the simulation is a simple solution but relevant and adequate. It is only heat transfer concept considered and ignored the solidification kinetics. The development of reliable specific models describing such solidification kinetics in the presence of nucleation and crystal growth is a current research area, especially in casting optimization to control porosities and shrinkage even microstructure. This research area, indeed, is reliable for that purpose but costly is due to advanced casting software required, complicated computer program algorithms and very long iteration process that so intricate. Nevertheless, our simulation is though so simple, when validated and compared with the experiment results have confirmed on the engineering judgment with obey the equilibrium phase diagram of iron-carbide based on the eutectic transformation. This statement can be explained through Figure 7 and Figure 8 where two sketches of curves describing phase diagram of Fe-C (black continuous line) and cooling curve of numerical result (red dash-line) are shown. The chemical composition of gray cast iron used in this experiment occurs at the eutectic composition where in the phase diagram coincide with a carbon equivalent 4.3% (3.6 %C + (2 %Si + 0.06 %P)/3). The relationship between cooling curve and phase diagram is based on the shape of the curve. In the upper cooling curve (continuous line), initial and end of solidification is shown on the solidification phase area. If the first solidification occurs at eutectic temperature 1150^{0}C, the microstructure of join is normal flake graphite (type A) on pearlite matrix. If the first solidification occurs below the eutectic temperature 1127^{0}C or lower, the microstructure found is carbide network as white cast iron (dashed line) and if it is in between both temperatures above, it will find fine flake graphite (type D, see Figure 6).

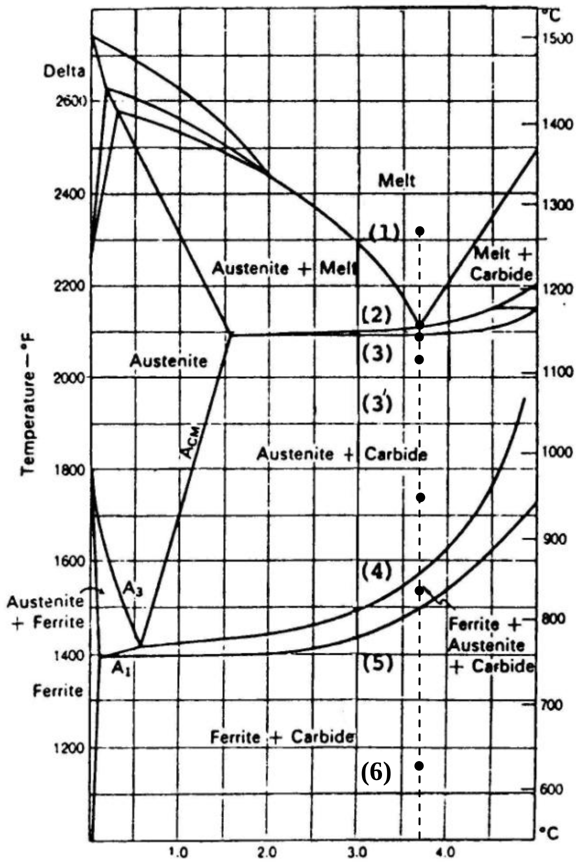


Figure 7: Pseudo-binary of phase diagram of Fe-C and eutectic phase transformation related to Figure 8.

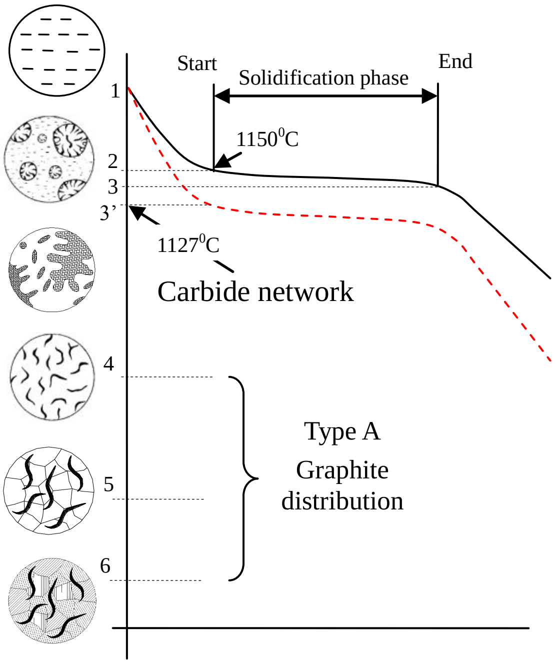


Figure 8: Cooling curve resulted from numerical simulation (red dash-line) to predict microstructure of repair join by the Turbulence Flow Casting method (related to phase diagram of Fe-C, Figure 7)

The example of cooling curve representing the microstructure prediction resulted from the numerical simulation is depicted in Figure 9. The type-A graphite on gray cast iron is obtained because of first solidification is upper the eutectic transformation. Type-D graphite was obtained from the curve which faster cooling rate than type-A so that the graphite form for this type is very fine in ferrite matrix, commonly called as undercooled graphite. White cast iron, obtained from fastest cooling rate, is the most undesirable microstructure in engineering components since very hard and brittle.

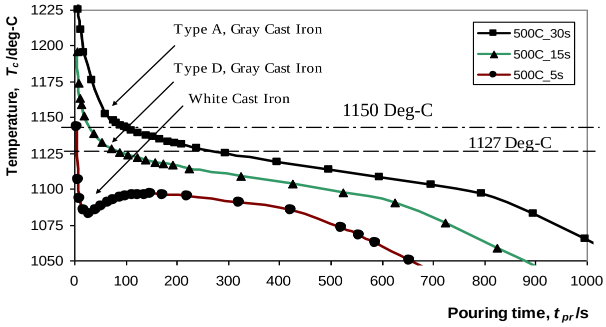


Figure 9: Cooling curve, resulted from the solidification simulation.

3.3 Comparison between Experiment and Numerical Investigation

3.3.1 Melting

The melting depths resulted from the experiments and numerical simulations have agreed for practical purpose since the difference of both results is only about 2 - 5% (see Figure 10). From heat transfer point of view, this error is the cause of using absolute number of preheating temperature when computer simulation, but contrariwise, during practice it has a temperature range. In addition, it may be influenced by pouring temperature which is not in exact value but in certain temperature range also.

3.3.2 Solidification

Microstructures map, in the Figure 11, is resulted from the experimental and numerical investigation. Arrow marks sign that both of investigation has agreed. Minus marks are three different data resulting from both investigation, it may not accurate in measuring pouring and preheating temperatures when the experiment done. The remaining data, no mark, are resulted from the simulation. For succesful repair, the optimum temperature and time are in between 500-700^{0}C and 10-15 s respectively. These parameters also could be selected according to the purpose and condition of the components. For examples, if it is required low preheating temperature let say 100^{0}C, the time consuming is 25 s and the microstructure obtained is type-D of gray cast iron. For this selection, it will increase melting depth (see Figure 10) of defect surface so that preheating temperature should be increased but the pouring time should be decreased. A proper selection of those parameters and cost compromise will determine succesful repair of the components.

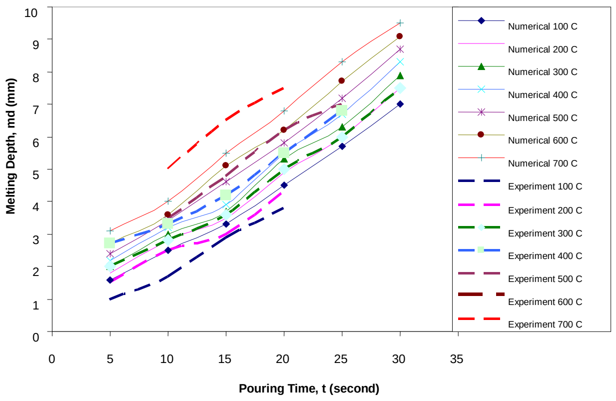
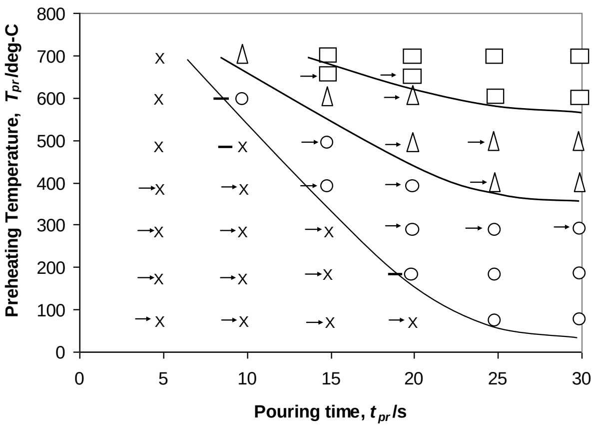


Figure 10: Melting depth comparison, resulted from the experimental and numerical investigation.



X *= White cast iron,* ***Circle*** *= type-D,* ***Triangle*** *= type D/A, and* ***Rectangular*** *= type-A graphite*

Arrow *= investigations agreed,* ***Minus mark*** *= not agreed,* ***No remarks*** *= simulation results*

Figure 11: Microstructure map, resulted from the experiment and numerical investigation.

4 CONCLUSION

A numerical model can be used for simulating a repair process by Turbulence Flow Casting method. Microstructure type is greatly affected by preheating temperature and pouring time. The modeling of melting and solidification enables to obtain melting depths and microstructures, so the number of data representing the experiment can be improved. Moreover, it will enrich the whole experiment results and analysis, reduce cost and less time consuming.

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