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Cooling Rate Analysis of Thin Wall Ductile Iron Using Microstructure Examination and Simulation

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Abstract. Cooling rate plays an important role in thin wall ductile iron solidification, due to their thickness. Casting simulation is used as a tool to estimate the cooling rate. In the other hand, every microstructure has its own cooling rate. This paper explores the similarity of solidification mechanism between simulation and graphite characteristics. Three types of casting design simulated and produced. Solidification mechanism is analyzed based on cooling rate sequence and trend line matching. Temperature gradient and thermocouple function represent simulation while graphite characteristic represent experiment. The result shows that similarity in solidification mechanism is not found between simulations with experiment due to lack of parameters in both sides.

Introduction

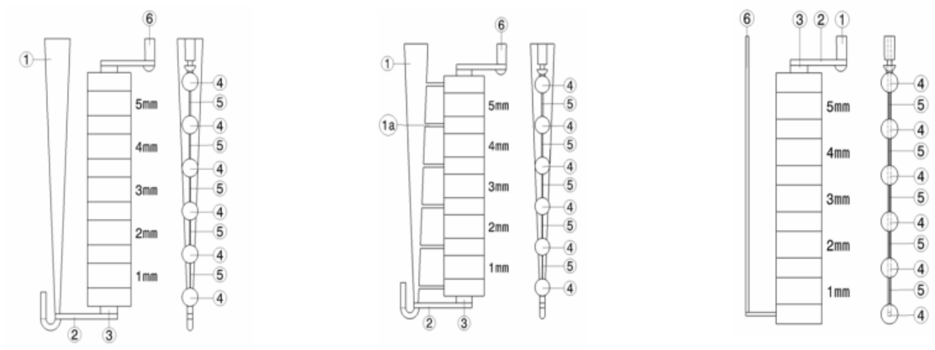
Thin wall casting is a casting process that produces casting product with thickness lower than 5 mm. This method makes ductile iron able to compete with aluminium in term of weight. Work by Soedarsono et al [1] and Suharno et al [2] showed that thin wall ductile iron (TWDI) can reach up to 1.0 mm thickness. The thinnest part ever made in TWDI is 1.0 mm [1-3]. Cooling rate becomes the critical issue due to thickness characteristic of TWDI especially when it comes to complex designs. Microstructures form based on its cooling rate. Carbide has the highest cooling rate and ferrite has the lowest. In producing TWDI, carbides should be avoided due to its detrimental to properties. While thin parts tend to form carbides.

Casting simulation becomes an important tool to deal with it. Simulation holds important role in casting process because it helps the designers to see how their casting designs result and reduced trial and error in real casting. Simulation of the design uses in producing TWDI will ensure the quality of the casting product. However, in its first application, the software needs adjustment and calibration to match the product. Juretzko and Stefanescu [4] used three types of commercial casting simulations during their research; they are NovaFlow&Solid, MagmaSoft, and ProCast. Work by Wooley et al [5] utilized MagmaSoft software to predict and solve the problems of micro shrinkage in TWDI. Other simulation software is Z-Cast. Z-Cast is developed by KITECH – South Korea. It offers all functions to estimate the mould filling processes and metal solidification.

This paper explores similarity of simulation with experiment result of solidification mechanism in producing TWDI.

Experimental Method

The casting designs (refer to Fig. 1) simulated with Z-Cast version 2.5. Simulation process consists of two step, that is filling and solidification. The results were analyzed in two ways. First are analyzed based on temperature gradient showed in legend and the second one based on thermocouple function.



T1 T2 T3

Fig. 1 Casting design.

1. down sprue 1a. supporting gate 2. runner 3. ingate 4. riser 5. plate 6. gas tunnel

The experiment conducted on foundry scale. The moulds made from furan sand. The metal cast was ductile iron grade FCD450. Fe-Si-6Mg used as nodularizing agent in sandwich method. Tapping temperature was 1500^{O}C. Inoculants type S70 used with its composition of 1.5%Ca; 72.95%Si; 0.86%Al; 2.1%Ba. The inoculants placed in the ladle. For the first batch (P1), the pouring temperatures were 1393^{O}C for T1, 1398^{O}C for T2 and 1379^{O}C for T3. While for the second (P5) was 1298^{O}C for T1 only.

Similarity between simulation and experiment was determined based on cooling rate sequence and trend line matches. Simulation was analyzed based on temperature gradient and thermocouple function while experiment was analyzed based on graphite characteristic, which consist of volume fraction of carbide presences (C), nodule count (NC), and graphite nodularity (N).

Result And Discussion

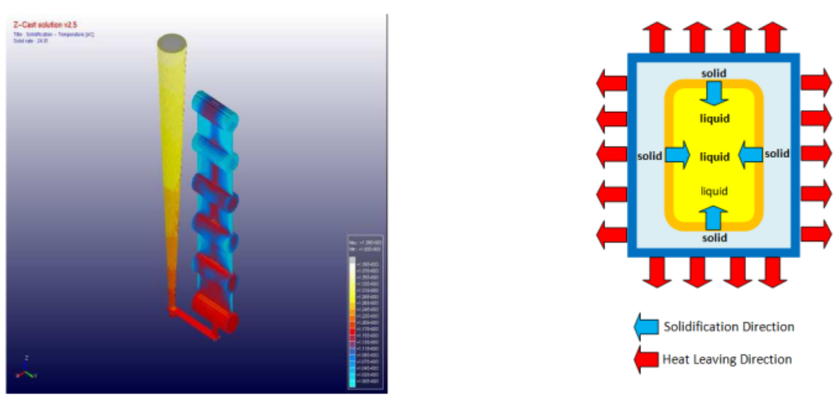


Fig. 2 Heat transfer scheme.

Solidification simulation (Refer to Fig. 2 – Left) shows that blue colour is forming from edge to centre in horizontal direction. This is representing solidification direction. Blue colour represents lower temperature compares to red. In one colour circle, lighter colour means lower temperature. Based on this result, schematic heat transfer is drawn (Refer to Fig. 2 – Right). Red arrows represent heat, while blue arrows represent solidification direction. Heat is leaving the cast product by convection and conduction. The direction of heat leaving is opposite with solidification direction.

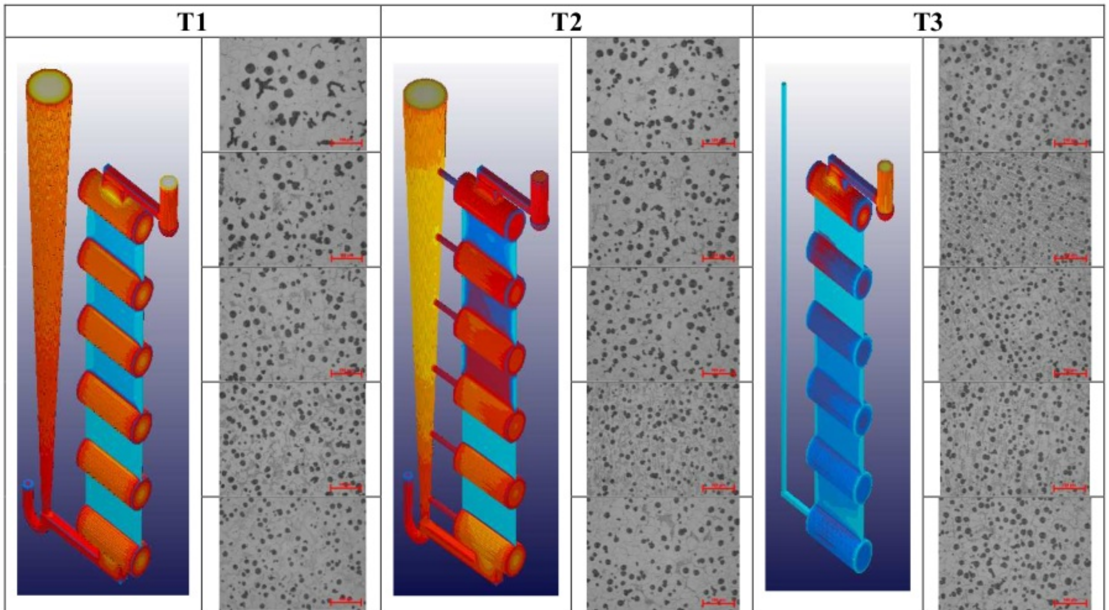


Fig. 3 Result of solidification simulation and micrograph taken from the each plat from different thickness

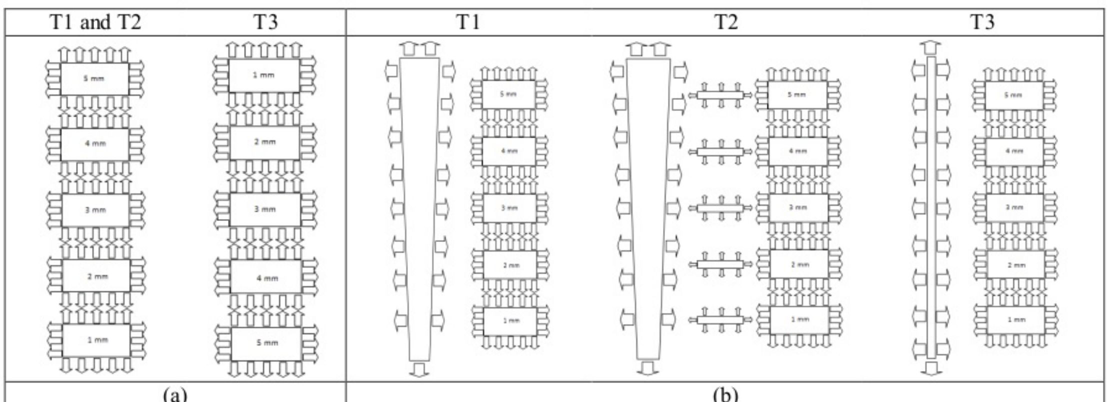


Fig. 4 Heat transfer mechanism
⇨ indicates heat release

Based on simulation results (Refer to Fig. 3) for T1 model the sequence of cooling rate is plate with thickness of 1 mm, then 2 mm, 5 mm, 4 mm, and the last is 3 mm. This sequence also applies for T2 and T3 model. It happens due to position of each plate, which is closely related to heat transfer. Plates with 1 and 5 mm thicknesses have five sides of heat release and one side of heat release and absorb. While Plates with 2, 4, and 3 mm thicknesses have only four sides of heat release and two side of heat release and absorb (Refer to Fig. 4.a). Comparing between the models, T3 has the highest cooling rate, follows by T1. T2 has the lowest cooling rate due to the presence of supporting gate. These are related to heat transfer (Refer to Fig. 4.b).

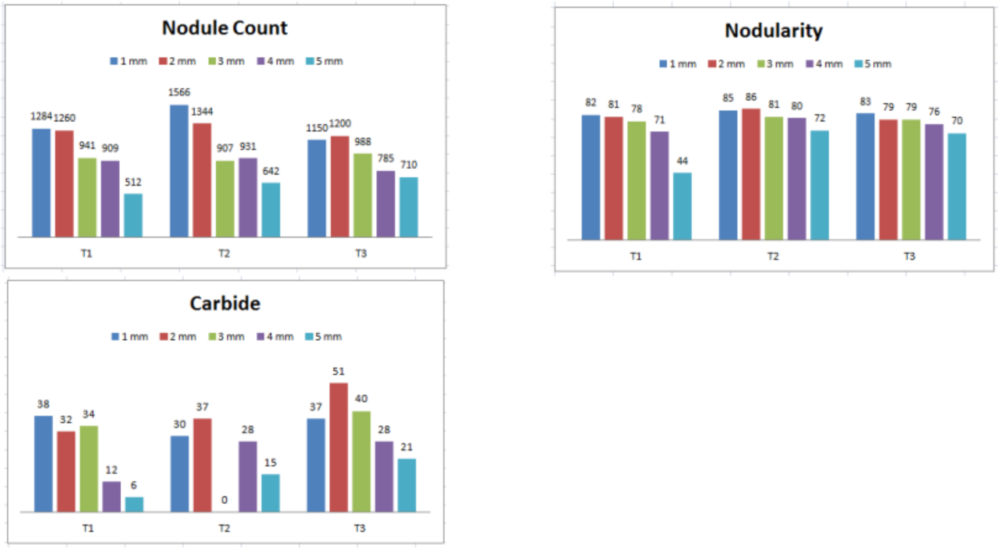
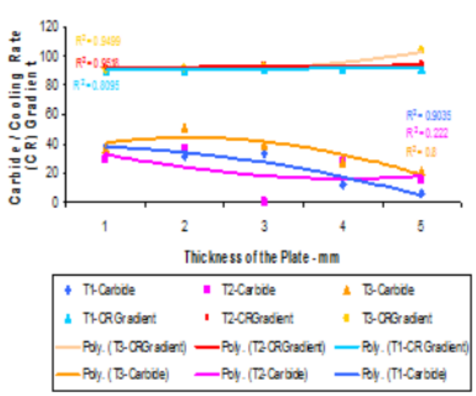
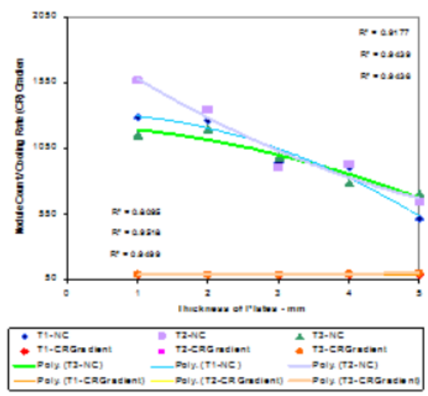


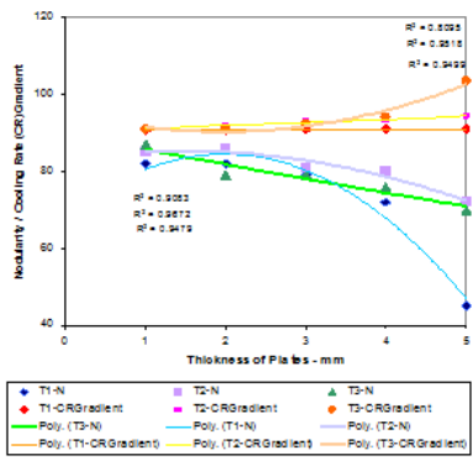
Fig. 5 Graphite characteristics



CR: Thermocouple function with carbide



CR: Thermocouple function with nodule count



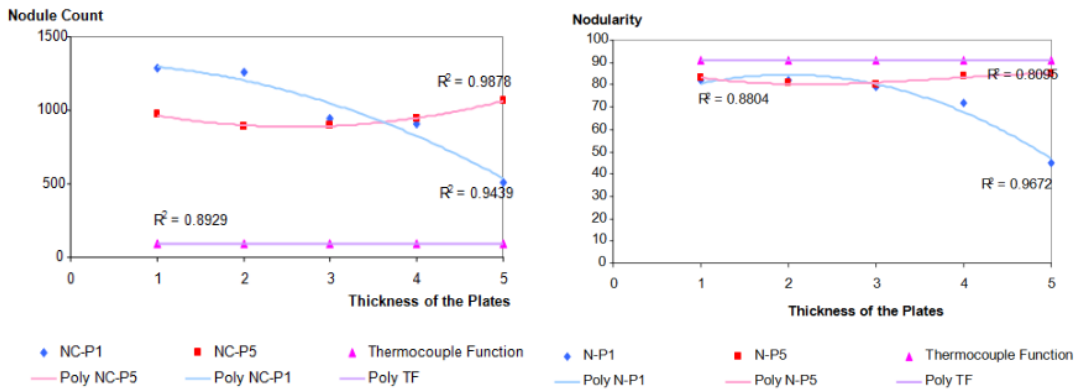
CR: Thermocouple function with nodularity

Fig. 6 Comparison of Cooling Rate (CR) curve trend :
Thermocouple functions (simulation) to microstructure (experimental)

The presence of carbides, nodule counts, and nodularity can determine cooling rate [6]. Higher nodule counts indicate as higher cooling rate. This condition will last until the maximum cooling rate is reach and after that, the nodule graphite will turn to carbides. From that point, the carbides presence will increase as the cooling rate increase. Carbides has higher cooling rate than graphite. Quantitative microstructure examination results for nodule count (Refer to Fig. 5) generally show same trend of cooling rate for all models. There is diversity but they all below 5%. Based on nodule counts the sequence of cooling rate from the fastest is plate with thickness of 1mm, 2mm, 3mm, 4mm, and 5mm. Nodularity also presents similar trend as nodule count. This is strengthening the cooling rate sequence established from nodule counts. While conclusion cannot withdraw from the quantitative examination of carbides, since they are not showing any specific trend.

Different sequences of cooling rate are obtained from simulation and experiment. Simulation sequence is 1mm, 2mm, 5mm, 4mm, 3mm experiment is 1mm, 2mm, 3mm, 4mm, 5mm.

In the second analysis trend line is use to define similarity between simulation with experiment result. It applied to thermocouple function and quantitative microstructure examination results. When polynomial trend line is applied to every curve (refer to Fig. 5), the results show it only fits for carbide presence in T2 (R^2=0.222). The R^2 value for the other curves lay between 0.80 with 0.95. The trend lines do not show similarity between simulation and experiment.



Nodule count to cooling rate trends Nodularity to cooling rate trends

Fig. 7 Cooling rate trend of t1 sample

Differences in quantitative results of T1 are found in the experiment. The differences are happening in samples from first (P1) and fifth (P5) pouring (refer to Fig. 6). This is happen due to disappearance of skin effect. Simulation does not note this condition. Mainly trend lines apply to experiment results do not similar to simulation. However, similarity is found in trend line of simulation and nodularity. Unlike nodule count, slight changes in cooling rate will not disturb nodularity. Nodularity will only be change if cooling rate is drastically changes too fast or too slow.

The findings show that graphite characteristics alone are not enough to determine cooling rate. Javaid et al [7] support this finding. Algarsamy [8] note that matrix influences mechanical properties of ductile iron. While cooling rate influence matrix and cooling rate is determined by chemical composition and wall thickness. Algarsamy also note that reversed condition runs between nodule graphite and matrix with cooling rate. Based on that, Algarsamy concludes that final matrix, nodule count, and chemical composition are the parameters to determine cooling rate. However, Van de Velde [9] stated that the focus in discussing solidification of ductile iron is lies only in graphite formation while the matrix is neglected. Pedersen and Tiedje [10] do not find similarity between simulation and experiment result in their 8 mm thickness plate. Juretzko and Stefanescu [4] concluded that simulation did help but adjustment and calibration should be performed prior to the experiment. Z-cast simulation calculates in macro scale and established base only on heat transfer. Z-cast simulation does not include micro scale such as phases changes in the software calculation.

Conclusions

Similarity of solidification mechanism based on cooling rate sequence and trend line matching between simulation with experiment results are not found since the simulation calculation is only based on heat transfer and the experimental work is only based on graphite characteristics. However, nodularity trend line for T1 model fifth pouring (T1P5) shows slight similarity with simulation trend line.

Further simulation should be focused on utilization of micro-scale modelling which included phase changing in the calculation.

Acknowledgement

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