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A management on mesh modelling for finite element analysis in casting simulation

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ABSTRACT

Purpose: In this paper we present a finite element mesh management technique applied to analyze thermal stress distribution of mushy region including molten materials and solidifying shell.
Design/methodology/approach: In this study we terminated and eliminated the finite elements representing molten materials on the element list. When they became cooler than the liquidus temperature, the deleted elements were recreated.
Findings: We considered temperature-dependent material properties during simulation and adopted hybrid FDM/FEM method for enhancing accuracy: We validated the proposed technique by comparing with other methods. As results, the proposed method is found to effectively simulate real-time casting process.
Research limitations/implications: The resulting simulation of conventional methods should induce errors on estimating residual stress of the cast subjected to non-uniform cooling. For the stress analysis study of casting process before complete solidification, we introduce a special technique to treat molten parts in the numerical procedure. This study proposes a method reducing by several orders the elastic modulus of molten material through employing a reduction factor.
Practical implications: Conventional casting process simulations don’t consider stress due to complex rheological behavior of molten metals until the cast completely solidifies. Achieving uniform cooling rate in a whole cast body while solidifying must be an ideal casting process to avoid undesirable thermal distortion and stress in product which may induce hot tear and crack. Conventionally many prototyping tests should be conducted to this end and necessitate expensive costs.
Originality/value: In this study we propose a new technique of “Element Creation and Termination” which terminates (or removes) molten elements and creates them just after they cool down to lower than liquidus temperature. Notice that the previous methods do not remove but deactivate molten elements.
Keywords: Numerical techniques; Element creation and termination; Casting process; Thermal stress

1. Introduction

Casting is one of the most efficient manufacturing means in mass production for geometrically complex as well as precise products. Its high flexibility in metal forming process is a most favourable feature of this manufacturing technique. Achieving uniform cooling rate in a whole cast body while solidifying must be an ideal casting process to avoid undesirable thermal distortion and stress in product which may induce hot tear and crack. Conventionally many prototyping tests should be conducted to this end and necessitate expensive costs. For the last two decades, numerous computational techniques have been introduced in engineering community thanks to the success in developing computer hard wares of low cost and high quality, although there are still unresolved computational fields of multi-physics like casting process. With increasing demands for casting products, a computational method to be able to optimize casting process with reduced tests should have been a cost saver to the foundry industries. These days, simulation of the casting process is commonly considered as a favorable tool before undertaking mass production to understand solidification process in mold cavity, heat transfer between mold and cast, and contraction and deformation of cast.

Many research efforts have been made for simulating casting processes. Thomas et al. [1] developed a two-dimensional mathematical model to predict internal stress generated in a steel ingot during thermal processing, calculating thermal history and stress respectively by the finite element method (FEM). Grill et al. [2] used numerical methods in predicting the heat flow and the gap formed at the mold of a continuous slab caster. Williams et al. [3] presented a thermal model allowing phase change to occur in the body and considering elasto-visco-plastic constitutive relationship for creep effects. Chandra [4] investigated finite element based analysis in predicting hot tears, hot cracks, residual stresses and distortion in precision casting.

The complex rheological behavior of metals includes creep and progressive failure as well as elastic-plastic straining [5]. Thus due to their difficulties, stress analyses in most of casting processes are usually skipped until all the parts of the casting product have been completely solidified. However thermal stresses and strains would be induced in casting while phase transforming before the whole cast body completely finishes solidification. In addition, there have been reported many investigations on casting and thermo-elasto-plastic processes. [6-10]

For the stress analysis study of casting process before complete solidification, we introduce a special technique to treat molten parts in the numerical procedure. This study proposes a method reducing by several orders the elastic modulus of molten material through employing a reduction factor. Lewis and Ravindran [5] varied the properties of the liquid elements to prevent them from changing their volume and building significant stress. “Element birth and death” in the commercial program ANSYS is a similar technique for simulating welding process, which deactivates molten material with a huge reduction factor as multiplying it with material properties such as stiffness and conductivity. In addition, mass, damping, specific heat, and other effects are nullified for deactivating the liquid elements [11]. Analogous techniques presented in other commercial programs and their applications have been also studied [12]. Deactivated elements are regarded as molten because their stiffness is much lower than that of surrounding elements. This technique is used to easily model things influenced by phase changes. However, the reduction factor often induces convergence problems and some calculations have to be repeated with other values of reduction factor.

Hence in this study we propose a new technique of “Element Creation and Termination” which terminates (or removes) molten elements and creates them just after they cool down to lower than liquidus temperature. Notice that the previous methods do not remove but deactivate molten elements. In this study, material properties in mushy region are used to be temperature-dependent in accordance with their phases at the corresponding time step. Molten elements are removed and eliminated on the element list, which results in no adverse effects of reduction factor. This technique can also save the calculation time because the number of nodes and elements are reduced in the model. Besides, hybrid method [10] was used in this study to take both advantages of FDM and FEM; for stress analysis, the FEM is more effective than the FDM [12]. Remarkable advance in computational methods has been made along with rapid development of computer technology. In mechanical engineering, the finite difference method (FDM) is well known to be efficient in flow and temperature analysis whereas the finite element method (FEM) is mostly favored in stress analysis among many other methods. Desire to solve more complicate problem seeks more efficient way to best simulate multiphysics in a time.

In the hybrid method, FEM is preceded by FDM which simulates solidification temperature history; FEM is employed to calculate thermal strains by in interpolating the nodal temperatures by FDM onto the finite elements nodal data [13]. In the results, we compared this study with conventional techniques.

2. Description of the work methodology

“Element Creation and Termination” technique is applied to thermal stress analysis. The numerical procedure for creating and terminating elements is shown in the Figure 1. Elements with lower solidification fraction than a critical value are first terminated. The solidification fraction value (50% chosen for this study) should be set for terminating elements. 0% and 100% correspond to the respective liquidus and solidus. Molten elements are made to disappear on element list and hence their stiffness is not included in the global stiffness matrix for FEM.

Once when molten elements are terminated and deleted from the element list, new connectivity table must be written. To keep the procedure efficient, we adopted the ordering algorithms of RCM (Reverse Cuthill-McKee), for renumbering [15]. We may decide whether this renumbering option is active or not.

Similar to element terminating process, elements can be created when the effects of killed elements become appreciable after sufficiently solidified. When the elements are not completely solidified, the modulus of elasticity should be multiplied by a factor to reduce it by several orders. In addition, other properties are modified in accordance with temperature. Thermal loading to which elements are subjected are adjusted according to stress-strain relations, which is to prevent the development of the significant stress and strain. The criteria of how to determine the temperature-dependent material properties in the mushy zone will be discussed later in this paper.

3. Results and discussion

A simple model is selected for the verification of our study; model has geometry of 400*250mm with 50mm slot in the base together with two vertical cylinders on the top. The cast is SCMoSC1, and the mold material is sand. All of the material properties are assumed to be temperature-dependent. At the

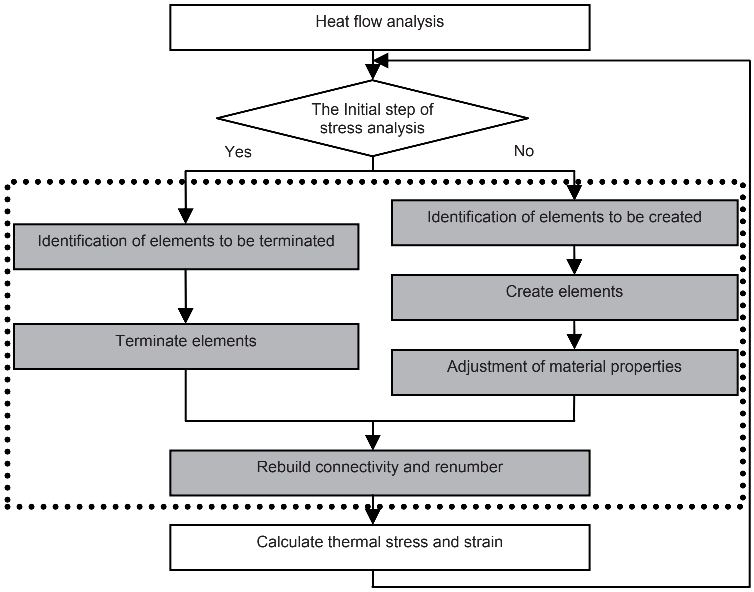

Fig. 1. Numerical procedure for creating and terminating elements in the algorithm

mushy zone, the modulus of elasticity is multiplied by a decreased factor corresponding to solidification fraction. A 4-node tetrahedron element is used for the finite element analysis. The number of elements and nodes for Figure 3 model are 28,461 and 6,435 respectively.

Temperature distribution data consists of 62 discrete time steps. Temperature field of the FD model is transferred to the FE model for stress analysis. It is assumed that the pouring temperature is 1,550˚C and the cast cool down to 100˚C. Figure 2 shows deformed shape. Table 1 is the summary of the analyses results.

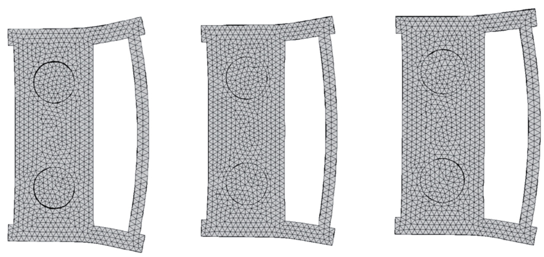

Fig. 2. Deformed shapes (×10 magnified)

As the above results shows, each value of stresses are similar but strains have considerable deviation of which maximum is 22%. These results prove that the level of strain which is generated before complete solidification is ineligible even if it is not significant. For that reason, we investigate stress generation and shape of deformations. (Figure 3)

In a conventional simulation of the casting process, the stress analysis is not commonly conducted until all parts of the casting product are completely solidified, which leads to poor estimation.

Table 1.
Computation results

	Conventional method		Earlier method		This study	
	max	min.	max	min.	max	min.
Disp x	3.31E-3	6.79 E-4	4.26E-3	(-) 5.76 E-4	4.25 E-3	(-) 6.44 E-4
Disp y	3.46E-3	(-) 3.52 E-3	4.02E-3	(-) 4.04 E-3	4.20 E-3	(-) 3.79 E-3
Disp z	2.00E-4	(-) 2.02 E-3	2.07E-4	(-) 2.09 E-3	2.08 E-4	(-) 2.09 E-3
σ_{xx}	6.15E8	(-) 5.15 E8	5.93E8	(-) 4.98 E8	6.04 E8	(-) 5.08 E8
σ_{yy}	3.99E8	(-) 2.85 E8	3.72E8	(-) 2.63 E8	3.84 E8	(-) 2.74 E8
σ_{zz}	1.60E8	(-) 5.88 E7	1.42E8	(-) 4.54 E7	1.51 E8	(-) 4.75 E7
von Mises	5.79E8	6.06 E6	5.60E8	6.25 E6	5.67 E8	6.33 E6

In this study, it is assumed that liquids and elements of which solidification fraction is lower than 50% are negligible. If the effects of removed elements were not negligible after enough solidification, they were simply created. At this moment, the modulus of elasticity is multiplied by a decrease factor to reduce by several orders because the elements are not completely solidified. Material properties depending on temperature and the corresponding phase are used as Decreased factor (10e-5 to 1) for elastic modulus in 50~100% mush zone ($T_{liquid} > T > T_{solid}$). This method oversimplifies the behaviors of metal in the mushy region. Therefore, we have studied and developed a numerical model which considers both: the time and the temperature-dependent characteristics of the rheological behavior of metals. It is expected that the simulation of the casting process can be much closer to the real-time phenomena if the numerical model comes to be in perfect harmony with our "Element Creation and Termination" technique.

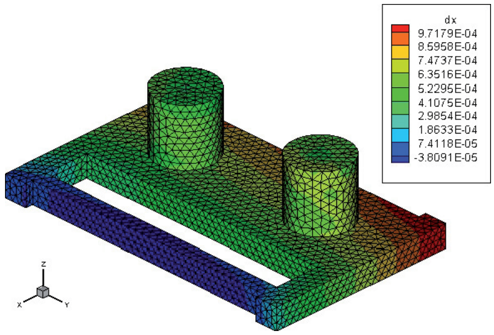

Fig. 3. Deformation the solidified whole body

4. Conclusions

We proposed and developed a new simulation technique, "Element Creation and Termination," for the casting process. It was verified with the numerical example and the results were compared with those of conventional methods. Using the proposed technique considering the behavior of molten and quasi-solid elements, we can overcome the difficulties arisen in thermal stress analysis. Additionally, the effects of generated constraints due to non-uniform cooling rates can be investigated more accurately. It is expected that we can obtain better results of stress analysis for the casting process if we accomplish the development of a numerical model for the time and temperature-dependent behaviors of materials in the mushy region, together with taking into account the effects of externally generated constraints.

Acknowledgements

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