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Finite Element Analysis of Direct Chill Casting using Concept of Element Birth and Death

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Abstract**: *A direct chill (DC) casting is a continuous casting process widely used in different industries. The aim of the work is to investigate thermal and mechanical stress formed during the direct chill casting process by a numerical method. A commercial software ANSYS mechanical APDL is used for the simulation. A moving mesh technique is employed for the development of ingot during the solidification process. An element birth and death concept is used to find out the deformation in ingot. The verification of the results is done with the results found in literature and found a good agreement. The developed model has admirable ability to predict the thermal and mechanical stress formed in direct chill casting process.***

Keyword**: *Finite Element (FE) Analysis, Element birth and death, Direct chill casting, heat transfer, stress.***

I. INTRODUCTION

Direct chill (DC) casting is one of the widely used continuous casting process in light weight processing technology. Direct chill casting is a technique for producing different shaped solid ingots and billets from non-ferrous metals and alloys especially copper, aluminium, magnesium. Aluminium and their alloys are the most usual material for the direct chill casting [1]. In the process of direct chilling, ingots are subjected to rapid cooling by bottom block and water sprays along the sides of the wall which cause sufficient solidification of the liquid metal around the outer surface of the mould. The liquid metal acquire the shape of the mould with sufficient mechanical strength [1]. Thermal and mechanical stresses are formed due to the direct cooling from water spray during the direct chill (DC) casting process. This stress develops cracks which cause failures in ingots [1], [2]. A mechanism of solidification and cooling of liquid metals is very important for successful cast billets and ingots. A schematic of the direct chill casting is shown in figure 1. Typically A liquid metals are cooled below their freezing point before solidification takes place. The crystal growth of liquid metal depends on the temperature of the surrounding material. The temperature at the surface of the mould is far lesser than the liquid metal, hence the solidification is faster at the mould surface. The liquid metal temperature is higher at the center of the ingot than the mould surface hence a solid

phase can be seen at the surface of the mould and liquid phase at the center of the ingot. This can be seen in figure 1 which causes the two separate phases into the ingot (solid ingot ad liquid ingot). Various experimental and numerical techniques were used to analyze the effects and process of direct chill casting process. A FEA and CFD analysis techniques can easily predicts the thermal and mechanical behavior during the direct chill casting process [3]-[6]. A heat transfer through conduction and solidification governing equations are used for the FEA and CFD analysis of direct chill casting process. Loon et al. [3] demonstrated a CFD model to identify the solid-liquid interface and heat flow for various casting speeds. There are several compositional changes occur in solid-liquid phase due to the concentration in their interface which causes a base to curl upward. This phenomena is known as "butt curl" which will further affect surface contact between ingot and bottom block. This will develop thermal and mechanical stresses in ingot leading to cracks and tears. The direct chill casting technique is commonly used due to their benefits such as the reduction in centerline segregation, a better-quality homogeneous structure, better mechanical properties and lower and faster production cost [1]. However, the process having the limitations such as hot tearing, poor surface quality and macro segregation [7]-[9].

A study of failures due to thermal and mechanical stresses occurs in the ingots are the attraction of the researchers. Numerical analysis with the help of mathematical model or commercial software was presented in literature. Li et al. [4] developed a coupled coupled finite element model (CON2D) to analysis the shell behavior in continuous casting process for still. Their model can be used to predict the temperature, shape and thermal stress during the casting process. A heat conduction, solidification, elastic-viscoplastic creep constitutive equation were solved numerically. Validation of the numerical model was done by comparing the results of both temperature and stress. Weckman and Niessen [10] solved steady state thermal problem of D. C. casting using finite element technique for A6063 aluminum material. An effective heat transfer coefficient were calculated for vertical position of ingot. Zhang et al. [11] did a CFD analysis in commercial software FLUENT using coupled modelling during low frequency electromagnetic D. C. casting.

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An electromagnetic field, fluid flow, heat transfer and solidification were captured by using this model. Luo and Zhang [12] investigated numerically the effect of flow pattern, temperature profiles, and solidification in DC casting. They developed a new uniform direct chill casting method using combining electromagnetic stirring and intercooling for aluminum alloy. The results of new UDC and normal direct chilling method are compared and concluded that, the remarkable changes in the flow pattern, temperature profile by the addition of annular electromagnetic stirring and intercooling method. WILLIAMS et al. [13] were predicted the deformation occurs at base of ingots and stress formation. They used moving mesh method to present growth of ingots in vertical direction. They concluded that butt curl did not seem to be sensitive to inlet flow conditions in casting excluding very high vertical inlet velocities. They suggested that the developed analytical model used to predict thermal behavior, stress, and distortion. Hao et al. [14] presented a finite element mathematical model for prediction of temperature in direct chill casting process. They used boundary conditions as primary and secondary cooling between block and billets to simulate model. The authors found, presented model can precisely reproduce heat transfer process over variety of casting conditions. Zaloznik et al. [15] did a numerical study investigate the effect of velocity, billet diameter, mould cooling temperature, on development of macrosegregation in direct chill casting by the use of finite volume method (FVM). They found, the above parameters have a significant impact on macrosegregation structure through thrmosolutal natural convection flow in liquid pool and depth of mushy zone. Wagstaff [16] examines the direct chill casting process by changing the different parameters, experimentally and numerically. When superheated alloy cools rapidly, nucleation of minor crystals formed at a temperature below liquidus temperature related to its structure. They mentioned, a structure of solid and liquid interface frequently changes with decrease in temperature of solid-liquid interface. Two layers (solid and liquid) can be seen between the mould surface and the center of the ingot due to the heat transfer occurs by temperature difference. Nowak et al. [17] were developed finite volume based numerical code for the simulation of macro-segregation during solidification in direct chill casting. The developed code has admirable ability to precisely resolve the thermal convection in the pertinent parameter range. Eskin et al. [9] were investigated analytical model to predict effect of sump profile, macrosegregation and shrinkage on direct chill casting (DC) process. They concluded that the increase in depth of sump causes increases macro-segregation. They found, the distance between liquid and solid isotherms in alloy billets governs degree of macro segregation in direct chill casting billets. Hongjun et al. [18] were simulated a two-dimensional ANSYS based mathematical model to predict thermal stress developed in direct chill casting process. They found surface quality and microstructure primarily depends upon thermal changes and flow pattern. Larger stress and strain values calculated near top of crystallizer. Turski et al. [19] verified a finite element based model (ALSIM) by predicting the residual stress within direct chill cast large size slab.

Different approaches to investigate the effect of different process parameters in direct chill casting are also reported in the previous works. Different alternative methods are also used to reduce the casting defects like mouldless casting using electromagnetic force and eddy current with a high frequency coil is proposed by Getselev, [20]. Hatic et al. [21] developed a mesh less comprehensive numerical model for the simulation of DC casting under low-frequency electromagnetic field [22]. Their model has the ability to capture the effect of low-frequency electromagnetic field on temperature, and liquid fraction. Tang et al. [23] developed comprehensive mathematical model based on combination of finite element and finite volume package in commercial software ANSYS. They described the interaction of multiple physics field like fluid flow, heat transfer, electromagnetic and solidification during annulus-electromagnetic direct chill.

Limited research work was found from the above literature on the concept of element birth and death concept in numerical analysis of direct chill casting process. The aim of the research work is a partial verification of a Finite Element Analysis (FEA) model developed for aluminum alloy in DC casting using a commercial software ANSYS 14.5. A thermal and mechanical coupled field analysis is performed using concept of element birth and death to simulate and validate the Direct Chill (DC) casting process in a commercial software ANSYS APDL. A moving mesh technique is used for the development of the ingot during the analysis of DC casting process. The grid generation for FE analysis is carried out using 20-node BRICK element with coupled ability. An aluminum alloy is considered for the simulation of DC casting process. Asymmetrical boundary conditions (BC) can be used for the simulations in DC casting process. The results found from the simulations are compared with the results available in literature and found a good agreement possible.

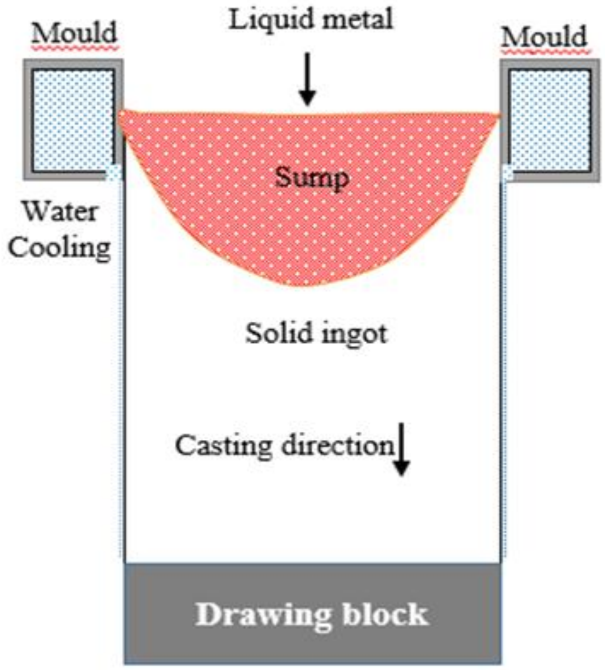

Fig. 1. Schematic diagram of direct chill casting.

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II. MODEL DESCRIPTION

An FEA model is developed to predict the temperature distribution and thermal stresses present in rectangular-shaped aluminum alloy ingot during the DC casting process. The final ingot in a DC casting process is expected to be larger than the pure elastic nature, hence the thermal stress relieved by the viscoelastic mechanism [2]. Transient structural-thermal simulation is performed to simulate the process of direct chill casting to study shrinkage of ingot. An aluminum alloy material is considered for the FEA analysis and their structural and thermal properties are shown in table 1.

A. Governing equations

The process of direct chill casting is governed by a coupled interactive phenomenon, which includes 1. Heat transfer from molten metal to mould, 2. Solidification and 3. Stress and 4. Deformation in the cooling ingot. The following assumptions to be considered for the heat transfer analysis during direct chill casting: 1. Thermal conductivity and the specific heat of the material varies with temperature, 2. Mould oscillation, curvature and segregation effect are neglected, 3. The surface temperature of the molten metal is equal to pouring temperature.

A direct chill (DC) casting process includes the heat transfer and solidification which can be simulated by solving transient heat conduction equation, force equilibrium for temperature and displacement, respectively. The governing partial differential equation used for the analysis for the solution of the transient thermal and structural problem is,

a. Energy Equation

$$\rho c\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + S \qquad (1)$$

Where, c is specific heat capacity, S is the heat source term, k is the thermal conductivity.

By applying the chain rule for equation 1 to isolate the specific heat and latent heat together for solidification,

$$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + S \qquad (2)$$

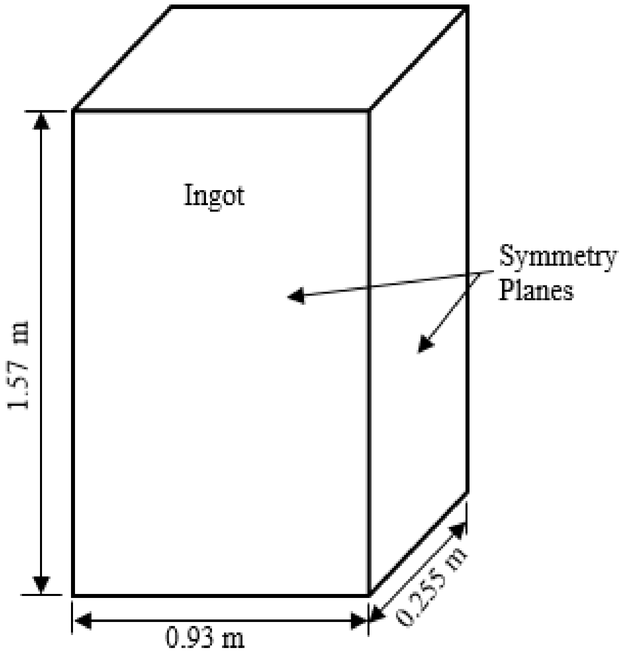
b. Stress model

The stress model can be solved by using a force equilibrium balance governing equation. The general form of force balance eq. is [4],

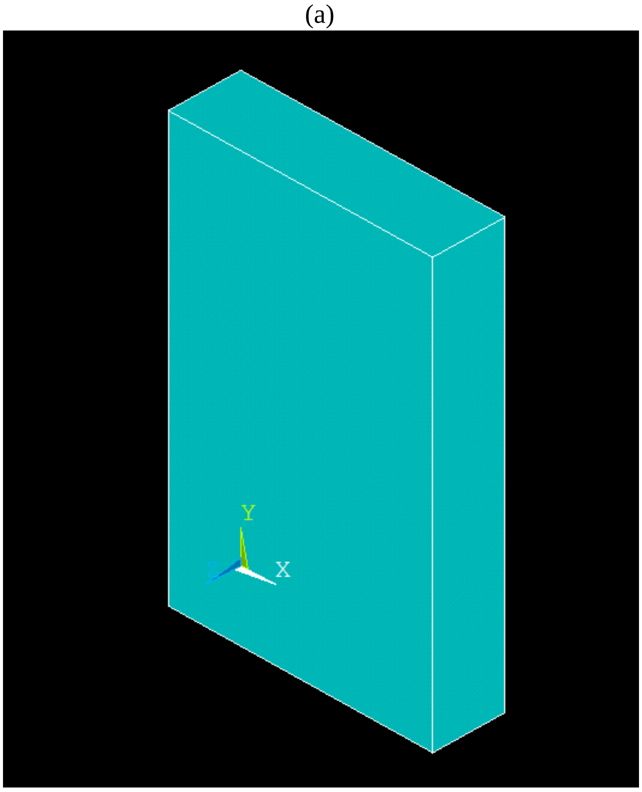
$$\nabla\cdot\sigma + \rho b = 0 \qquad (3)$$

B. Computational Domain

Figure 2 (a) represents the geometry and the computational domain considered for the analysis of the direct chill casting. A rectangular geometry aluminum ingot of dimensions of 1.57 m height, 0.93 m width, and thickness of 0.255 m will be considered as asymmetry option. Hence a computational geometry is selected as only one-quarter of the whole ingot geometry. In this work, mould and the drawing block are not moulded and considered to be constant surface. The initial height of the ingot is set to y = -0.07 m from the inlet base (y = 0) similar to the work presented by Williams et al. [8]. The computational domain can be drawn in a commercial software ANSYS APDL, and shown in figure 2 (b).



(a)



(b)

Fig. 2. (a) schematic geometry of Ingot, (b) Computational domain considered for the analysis

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Table-1. Thermal and structural properties of the aluminium alloy.

Solidus temperature	630 °C		Youngs modulus	68.2 GPa	≤ 25 °C
Liquidus temperature	658 °C			60.6 GPa	200 °C
Density	2650 kg/m3			51.8 GPa	400 °C
Dynamic viscosity	1 x 10^2 Pa/s			41.8 GPa	630 °C
Thermal conductivity	226 W/mK	≤ 630 °C		40.0 GPa	650 °C
	90 W/mK	≥ 658 °C		0.1 MPa	≥ 650.1 °C
Specific heat	905 J/kgK	≤ 27 °C	Poissons ratio	0.37	
	950 J/kgK	127 °C		3 x 10^5 / °C	≤ 650 °C
	998 J/kgK	227 °C		0	≥ 650.1 °C
	1043 J/kgK	327 °C	Yield stress	500 MPa	≤ 25 °C
	1090 J/kgK	427 °C		10 MPa	≥ 650.1 °C
	1135 J/kgK	≥ 527 °C	Fluidity	1.0 x $10^6 s^{-1}$	≤ 25 °C
	1181 J/kgK	630 °C		3.7 x $10^3 s^{-1}$	≥ 650.1 °C
	1086 J/kgK	≥ 658 °C	Strain-rate sensitivity	50	≤ 25 °C
Latent heat	358 kJ/kg			5	≥ 650.1 °C

C. Meshing

A direct chill (DC) casting process is a time-dependent phenomenon, hence transient analysis is necessary to capture the solidification and mechanical behavior simultaneously. A moving mesh approach is used to model the ingot generation. The initial mesh for the ingot is pre-defined so that it can be compressed in casting direction with top side fixed. The mesh moves downwards with the velocity equal to casting speed. The mesh spacing can be increased with the every time step, while thickness and width keep constant. FE analysis for the thermal and stress behaviour was carried out using 20-node BRICK element with coupled capability. Figure 3 shows the single element used for the analysis, A SOLID226 was used from ANSYS. A SOLID226 element has multi-physics capabilities. Structural-Thermal coupled physics was used to simulate temperature distribution and shrinkage of ingot at the end of ingot formation process. The domain consists of 3960 elements and 19013 nodes each size element is 62 x 42.5 x 35 mm as shown in Figure 4.

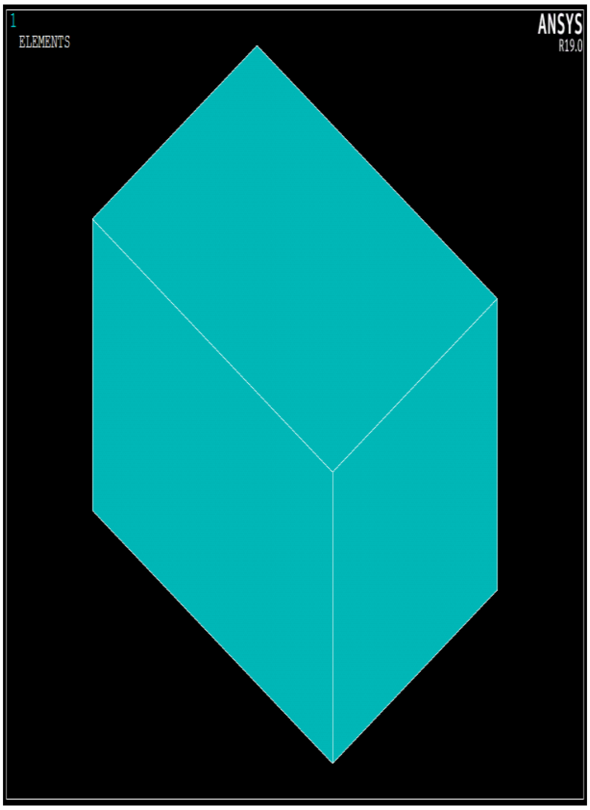

Fig. 3. A SOLID226 single element used for the analysis.

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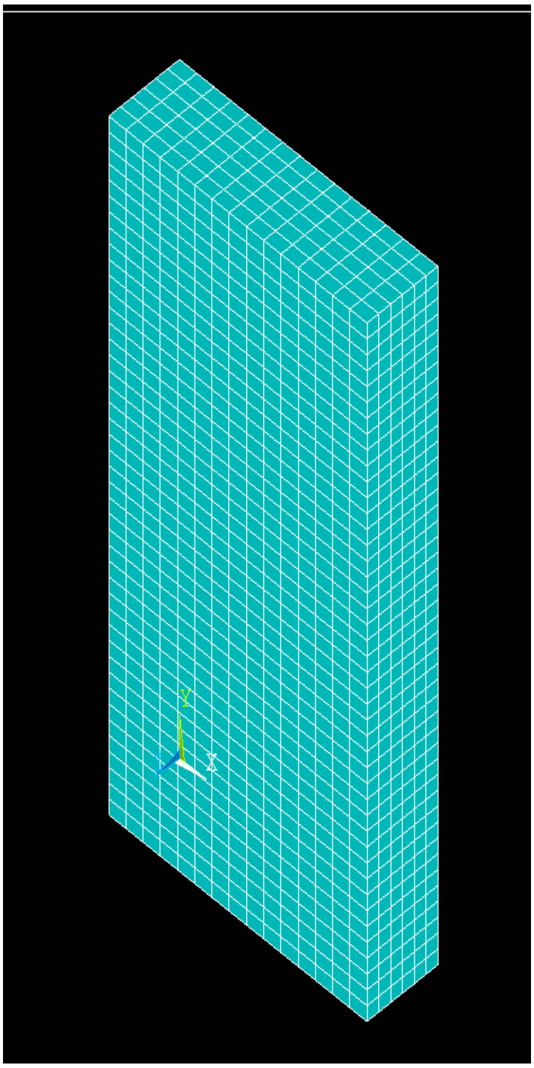

Fig. 4. Meshed model of computational domain in ANSYS

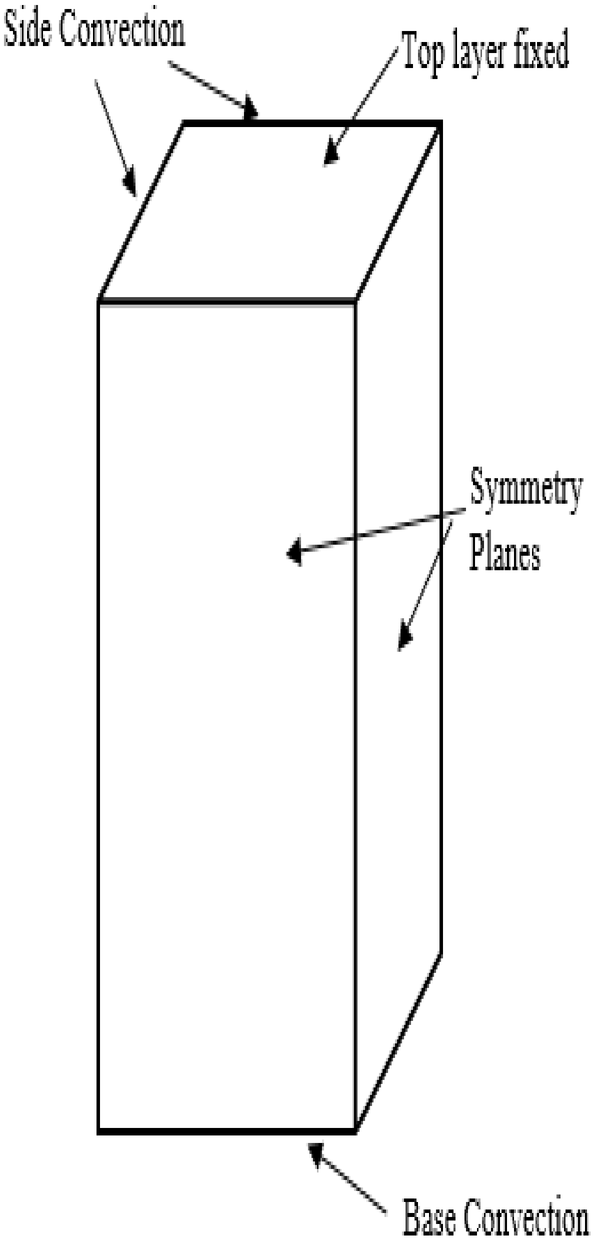

Fig. 5. Structural and thermal boundary conditions

D. Boundary Conditions

In order to investigate the formation of ingot, and the thermal and structural behaviour, a set of simulations are performed with different boundary conditions. Structural-thermal boundary conditions are imposed during coupled field simulation are as shown in Figure 5. Table 2 shows convection values at base and side faces of ingot.

Table-2. Heat-Transfer Coefficients at Base (h_{base}) and for Secondary Water Cooling (h_{sides})

T (^{0}C)	0	100	130	150	200	300	500	550	600	650
h_{base} (W/m^{2}K)	500	500	500	500	400	300	300	500	800	4000
h_{sides} (W/m^{2}k)	5000	8000	25000	25000	18000	10000	10000	10000	10000	10000

E. Numerical analysis

Based on the commercial software ANSYS APDL, An FEM and FVM method is used to solve the governing equations. In this analysis, it is assumed that one complete layer of material comes out and then it starts to solidify. The speed of the cast layer formation in numerical model is kept same as in actual casting speed (t = 25 min). The process of ingot layer formation is modeled with the concept of element birth by controlling the solidification temperature of the aluminium alloy (T_s = 630 ^{O}C). Initially, a complete ingot block (computational domain) is modelled and meshed in ANSYS APDL. At the beginning of casting process (t = 0 sec), all mesh elements are deactivated (element death), once the solidification temperature reached, a layer of ingot formation starts by activating the mesh element (element birth) with speed of casting. Figure 6 shows process of layer formation.

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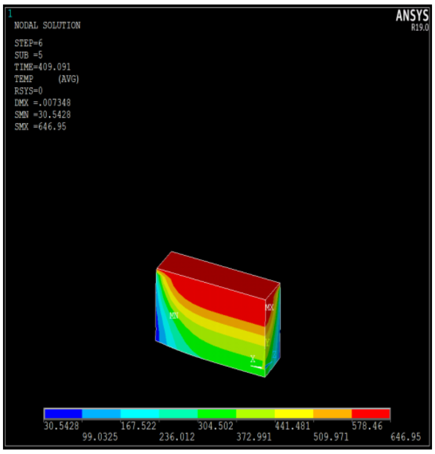
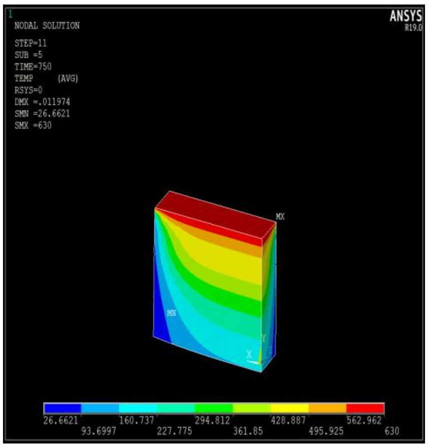
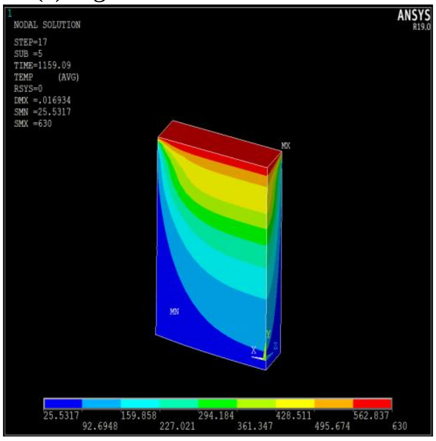


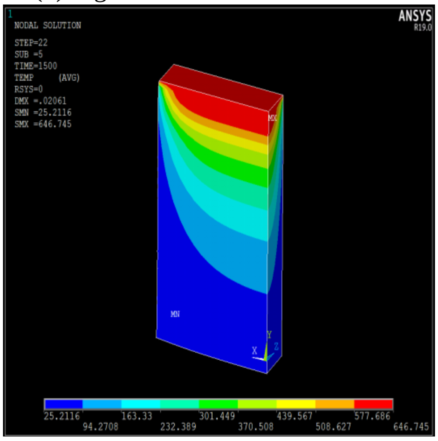
(a) Ingot formation at time *t* = 409 sec



(b) Ingot formation at time *t* = 750 sec



(c) Ingot formation at time *t* = 1159 sec

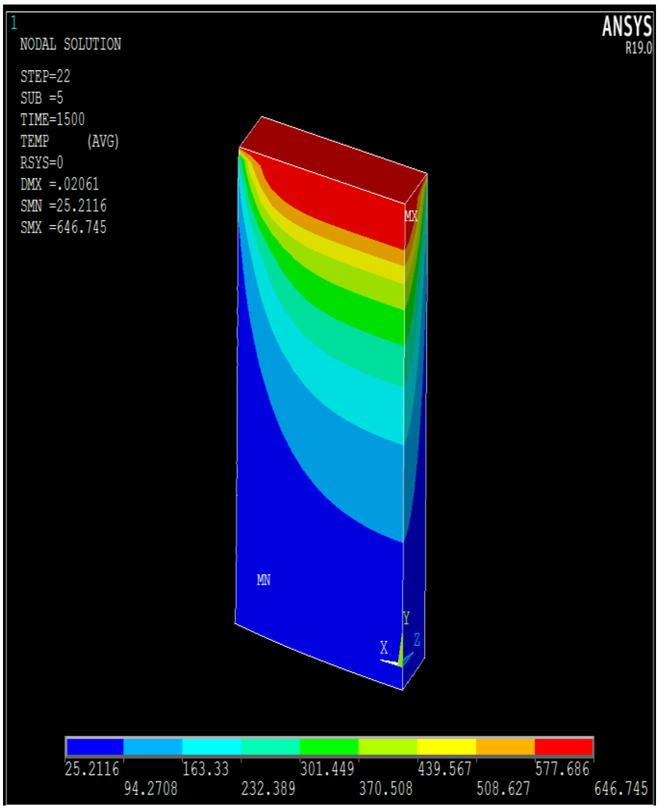


(d) Ingot formation at time *t* = 1500 sec

Fig. 6. Process of direct chill casting simulation by layer formation

III. RESULT AND DISCUSSION

A numerical model is set to examine the fluid, thermal structural behavior of direct chill casting process. A set of simulations performed to capture the results of the formation of the ingot and compare that results with results present in Williams et al. [8]. The dimensions and material properties were chosen similar of Williams et al. [8] for the analysis in order to compare the results. The simulations are done on the symmetry geometry of the one-quarter section of the total size. Figure 8 shows the contour of temperature distribution throughout the ingot after completion of casting process (t = 1500 sec). It can be seen in figure 7 (a), a maximum of 646.74 ^{0}C temperature is reached during the growth of ingot up to 1500 sec. The maximum temperature found in Williams et al. [8] is also shown in figure 7 (a) is 650 ^{0}C. Figure 8 presents the temperature contours with half symmetry along with width and length of the ingot. It can be observed from figure 8, the middle portion of the ingot seems to be hotter than the outside surface. It can be noted that, a liquid metal has a pool shaped structure at the centre of the ingot that can be found in results predicted by Williams et al. [8].



(a) Present Model

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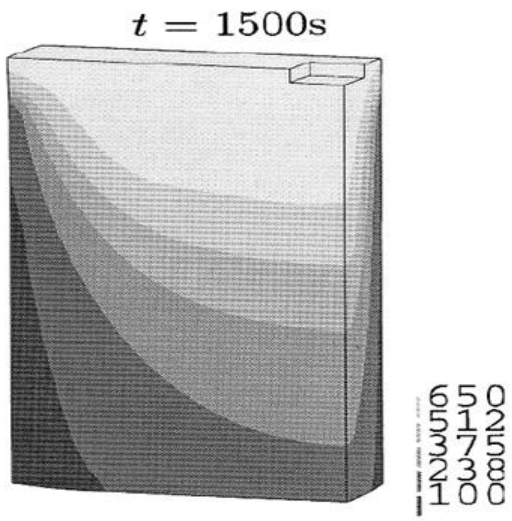


(b) Williams et al. [8]

Fig. 7 (a and b) comparison between temperature profile found in present model and Williams et al. [8] at time *t* = 1500 sec

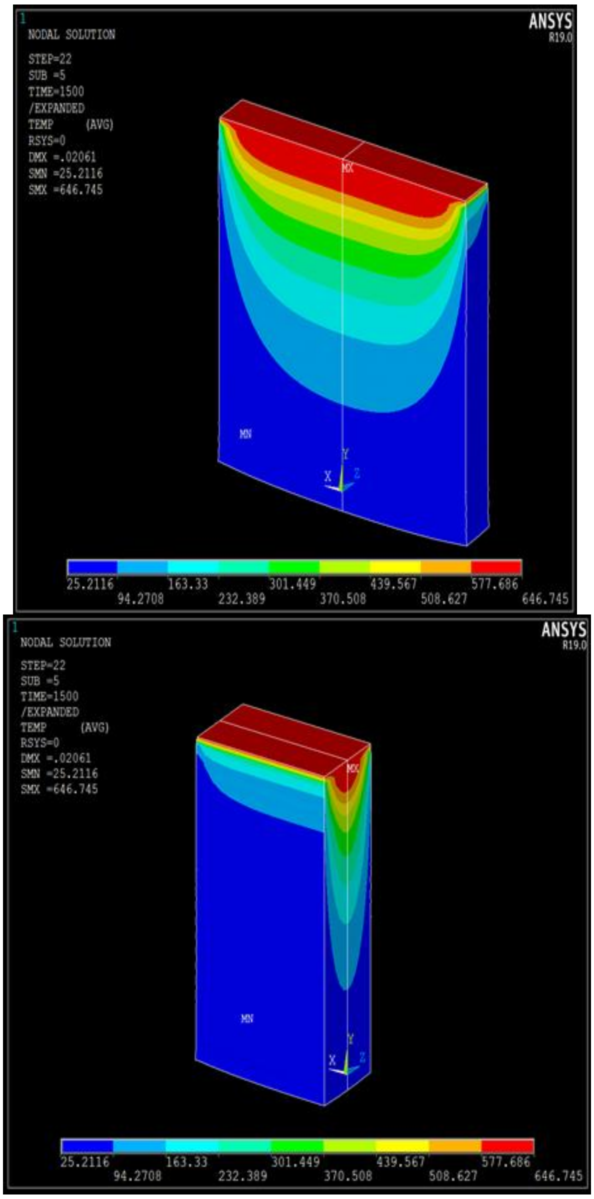
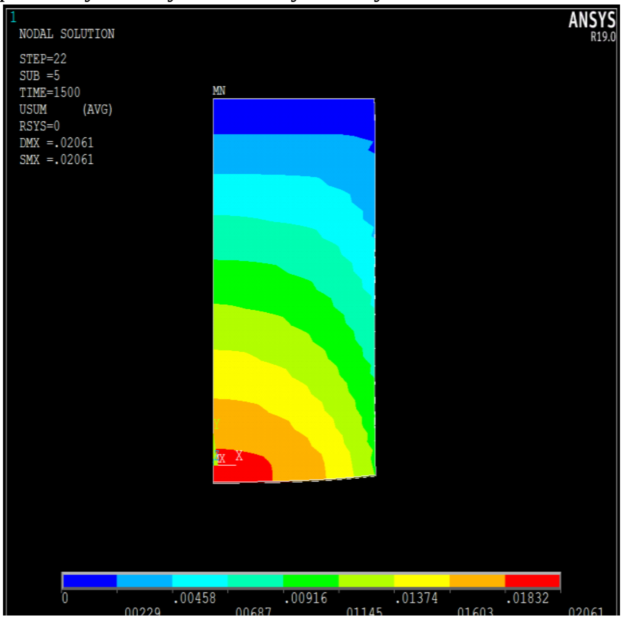
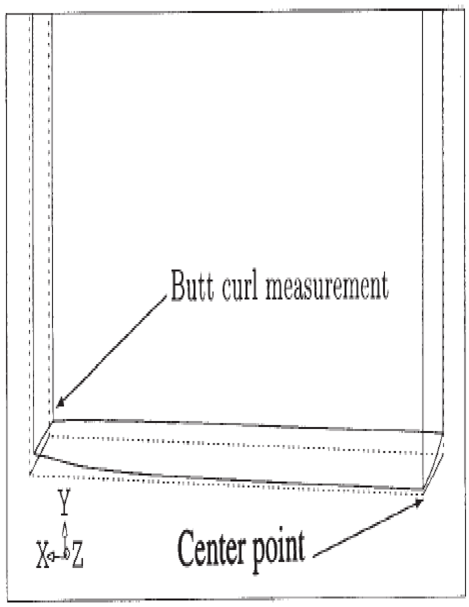


Fig. 8 Temperature profile with half symmetry along with width and length of the ingot.

To examine the overall deformation due to the thermal process during the DC casting, the displacement at the outer surface of the ingot is measured over the casting period in the simulation. The results present in Williams et al. [8] and the results found in developed model found good agreement and shown in figure 9 (a and b). The maximum deformation found in present model is 0.02 m while the deformation reported by Williams et al. [8] was 0.019 m. The above results proves that, the developed model can predict the thermal and mechanical behaviour of direct chill casting process. Figure 10 shows thermal expansion of the ingot just after completion of casting process. It shows images in quarter symmetry and half symmetry.



(a) Present model



(b) Williams et al. [8]

Fig. 9. Comparison of the results of thermal deformation of present model and the Williams et al. [8] during DC casting

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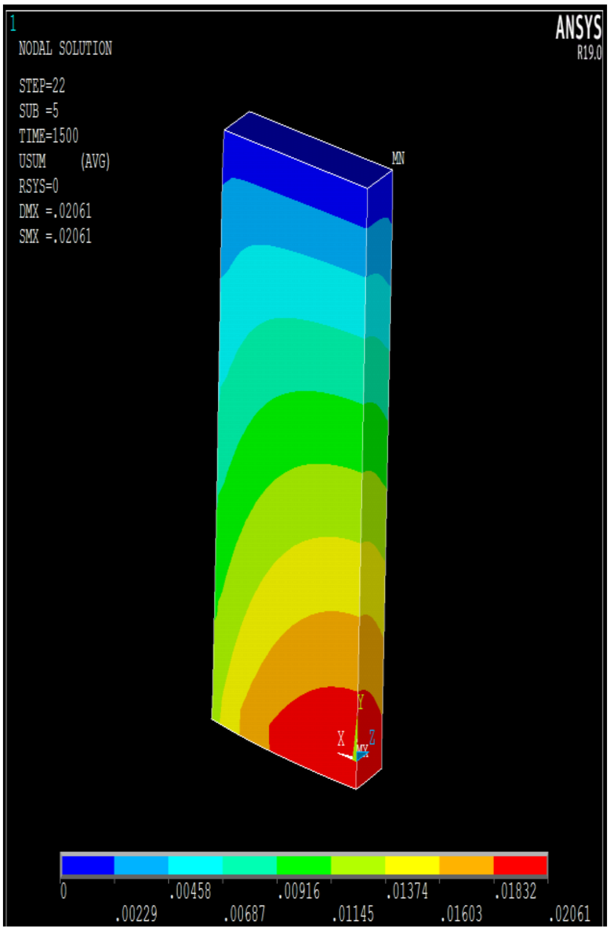
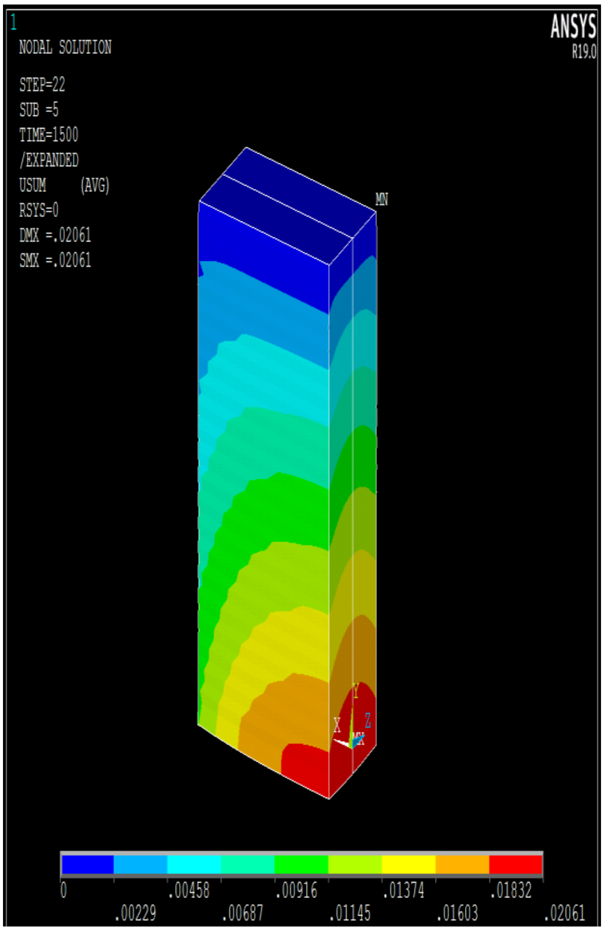
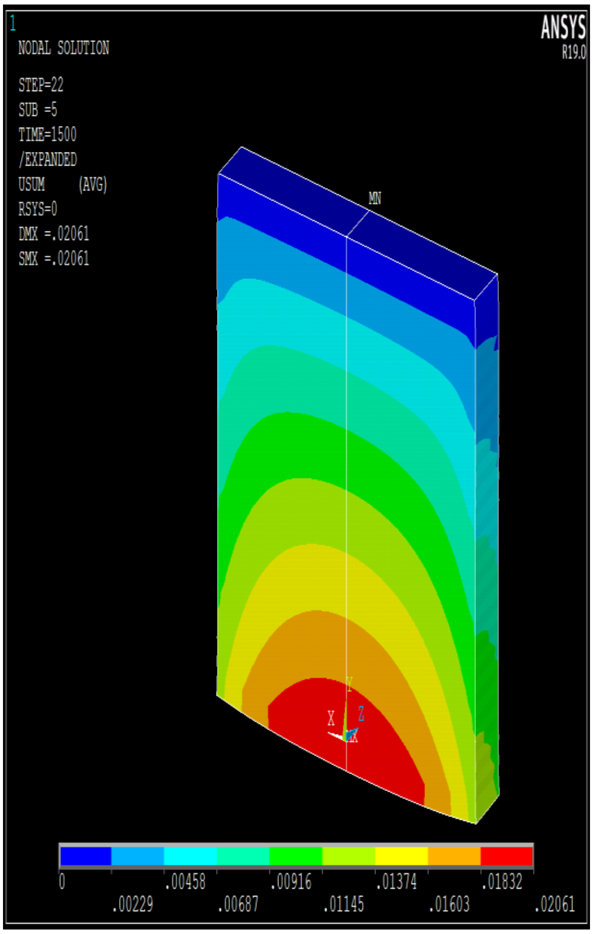


(a) Quarter Domain



(c) Quarter Domain along length

Fig. 10. shows the thermal expansion contours at time *t*= 1500 sec.



(b) Quarter Domain along width

IV. CONCLUSION

A FEA based numerical model has been developed and tested to study the thermal and mechanical behaviour of direct chill casting process. The governing equations of mass, momentum and energy along with volume of fluid equations are solved to predict the temperature profile over the time of casting process. The results found in present element birth and death based model have the good agreement with the results found in literature. From the above discussion, it is concluded that, the present model based on the element birth and death has shown the excellent ability to accurately resolve the thermal and mechanical behaviour of the direct chill casting process. The present model has the ability to of good grid generation and minimum error solution.

REFERENCES

1. Eskin, D.G., "Physical metallurgy of direct chill casting of aluminum alloys." CRC press2008.
2. Drezet, J.M. and Rappaz, M., "Modeling of ingot distortions during direct chill casting of aluminum alloys." Metallurgical and Materials Transactions A, 1996, 27(10), pp.3214-3225.
3. Loon, L.W., Reddy, S.S. and AK, P.R., "CFD simulation of direct chill casting process of magnesium alloy billets." Journal of Manufacturing Processes, 2019, 45, pp.447-454.
4. Li, C. and Thomas, B.G., (2004). "Thermomechanical finite-element model of shell behavior in continuous casting of steel." Metallurgical and MAterials transactions B, 35(6), pp.1151-1172.

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5. Lewis, R.W. and Ravindran, K., "Finite element simulation of metal casting." International journal for numerical methods in engineering, 2000, 47(1-3), pp.29-59.
6. Le, Q.C., Guo, S.J., Zhao, Z.H., Cui, J.Z. and Zhang, X.J., "Numerical simulation of electromagnetic DC casting of magnesium alloys." Journal of materials processing technology, 2007, 183(2-3), pp.194-201.
7. Combeau, H., Zaloznik, M. and Bedel, M., "Predictive capabilities of multiphysics and multiscale models in modeling solidification of steel ingots and DC casting of aluminum." Jom, 2016, 68(8), pp.2198-2206.
8. Založnik, M., "Modeling of macro segregation in direct chill casting (Doctoral dissertation," Univerza v Novi Gorici, Fakulteta za podiplomski študij), 2006.
9. Eskin, D.G., Du, Q. and Katgerman, L.,"Relationship between shrinkage-induced macro segregation and the sump profile upon direct-chill casting." Scripta Materialia, 2006, 55(8), pp.715-718.
10. Weckman, D.C. and Niessen, P., "A numerical simulation of the DC continuous casting process including nucleate boiling heat transfer." Metallurgical Transactions B, 1982, 13(4), pp.593-602.
11. Zhang, H., Nagaumi, H., Zuo, Y. and Cui, J., "Coupled modeling of electromagnetic field, fluid flow, heat transfer and solidification during low frequency electromagnetic casting of 7XXX aluminum alloys: Part 1: development of a mathematical model and comparison with experimental results." Materials Science and Engineering: A, 2007, 448(1-2), pp.189-203.
12. Luo, Y. and Zhang, Z., "Numerical modeling of annular electromagnetic stirring with intercooling in direct chill casting of 7005 aluminum alloy billet." Progress in Natural Science: Materials International, 2019, 29(1), pp.81-87.
13. Williams, A.J., Croft, T.N. and Cross, M., "Modeling of ingot development during the start-up phase of direct chill casting." Metallurgical and Materials Transactions B, 2003, 34(5), pp.727-734.
14. Hao, H., Maijer, D.M., Wells, M.A., Cockcroft, S.L., Sediako, D. and Hibbins, S., "Development and validation of a thermal model of the direct chill casting of AZ31 magnesium billets." Metallurgical and Materials Transactions A, 2004, 35(12), pp.3843-3854.
15. Zaloznik, M. and Sarler, B., "Modeling of macro segregation in direct-chill casting of aluminum alloys: Estimating the influence of casting parameters." Materials Science and Engineering: A, 2005, 413, pp.85-91.
16. Wagstaff, S.R., "Experimental observations and analysis of macro segregation in rolling slab ingots (Doctoral dissertation, Massachusetts Institute of Technology)." 2005.
17. Nowak, A.J., Białecki, R.A., Zaloznik, M., Xin, S. and Sarler, B., "Verification of a numerical model of macro segregation in direct chill casting." International Journal of Numerical Methods for Heat & Fluid Flow, 2008.
18. Hu, H., Zhang, D. and Yang, M., "Numerical simulation of thermal stress in cast billets made of AZ31 magnesium alloy during direct-chill casting." Journal of manufacturing processes, 2008 10(2), pp.82-88.
19. Turski, M., Paradowska, A., Zhang, S.Y., Mortensen, D., Fjaer, H., Grandfield, J., Davis, B. and DeLorme, R., "Validation of predicted residual stresses within direct chill cast magnesium alloy slab." Metallurgical and Materials Transactions A, 2012, 43(5), pp.1547-1557.
20. Getselev, Z.N., "Casting in an electromagnetic field." JOM, 1971, 23(10), pp.38-39.
21. Hatic, V., Mavric, B., Koznik, N. and Šarler, B., "Simulation of direct chill casting under the influence of a low-frequency electromagnetic field." Applied Mathematical Modelling, 2018, 54, pp.170-188.
22. Vertnik, R., Zaloznik, M. and Sarler, B., "Solution of transient direct-chill aluminium billet casting problem with simultaneous material and interphase moving boundaries by a meshless method." Engineering Analysis with Boundary Elements, 2006, 30(10), pp.847-855.
23. Tang, M.O., Jun, X., Zhang, Z.F. and Bai, Y.L., "Effects of annulus gap on flow and temperature field in electromagnetic direct chill casting process." Transactions of Nonferrous Metals Society of China, 2006, 21(5), pp.1123-1129.

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