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3D Numerical Simulation of 'Herringbone' Defective Ribbon formation in planar flow melt spinning process.

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ABSTRACT — The Puddle region where the molten metal is held by surface tension in the gap between nozzle and wheel is subjected to motion at the meniscus, which can lead to thickness variations that appears as casting lines or marks along the width of the ribbon. Many types of defects may be present on the surface of melt spun ribbon which include dimples, herringbone, waves, striations, etc. The wavy feature spanning the width of the ribbon which appeared periodically is discussed using 3D Numerical simulations. 3D Wheel along with the air domain is considered as the computational domains. VOF, energy and momentum equations are solved in the numerical simulation of two phase flow in the domains. Consistent with experimental observations, Herringbone formation is observed on the ribbon surface during 3D numerical simulations attributed to the pinning of Upstream meniscus of the puddle to the nozzle slit edge.

Index Terms — Planar Flow Melt Spinning, Herringbone defect, cross wave defect, Volume Of Fluid, pinning, Puddle, Meniscus,

1 INTRODUCTION

Melt spinning, also known as spin casting, has long found utility in amorphous material manufacture. Planar Flow Melt Spinning process (PFMS) is a technique for producing thin metallic foils or strips through rapid solidification process. A melt puddle is formed in the gap between the nozzle walls and the cooling wheel. Melt is ejected in the form of a ribbon from the under cooled puddle due to wheel rotation[1]. Fig [1] shows the schematic representation of the PFMS process. PFMS requires ribbons to be cast with good quality (e.g. uniform thickness, uniform surface quality). It is believed that vibrations of the upstream meniscus (USM) allow air bubbles to become entrained between the puddle and the wheel. The air pockets act as an insulator, reducing the rate of heat-transfer from the puddle to the wheel, locally reducing the ribbon thickness. Thus, the shape of the solidified metal on the wheel side is caused by the physical presence of air pockets, and the shape on the air-side is caused by reduced solidification rates due to the heat-transfer interruption caused by air entrainment. Various surface defects have been reported experimentally, and the cause is due to the instability of the puddle meniscus [2,3]. Casting lines in PFMS have been previously discussed. Carpenter and Steen [5] summarized a variety of ribbon surface textures. 'Dimpled' and 'striated' lines that form in a 50/50 Pb– Sn alloy are discussed [6], cross wave and Herringbone(HB) defects are reported [2,4]. It is reported that the HB is due to the pinning of USM at the nozzle inlet slit. Fig 1.b represents the schematics of HB defect on the ribbon. The current study focuses mainly on the time dependent behavior of the process, with particular emphasis on the dynamics of the molten melt puddle and ribbon surface quality. 3D numerical simulations are performed to study the puddle stability and ribbon surface quality with melt ejection velocity(V), wheel speed(ω) , nozzle wheel gap(G) ,Nozzle Slit breadth (b) , Nozzle slit width (w).

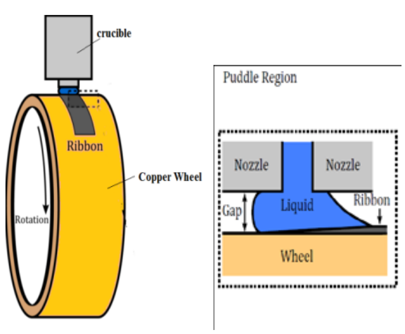

Figure1.a: Schematic of planar flow melt spinning and Puddle region (courtesy Anthony L. Altieri and Paul H. Steen et al[4])

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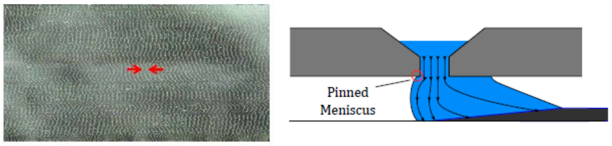


Fig 1.b: schematic of
Herringbone defective ribbon and Pinning Of USM to nozzle slit

2. Numerical Model:

3D numerical model is employed using ANSYS FLUENT software. Transient flow analysis of PFMS process is carried out with melt puddle fluid domain and copper wheel solid domain. Fig [2a,2b] shows the mesh system and boundary conditions of fluid and solid Domains. Inlet [A] represents the melt inlet velocity at the Nozzle slit width (w). Nozzle Walls [B] indicate the Left and Right Nozzle walls of the crucible. Air Domain [C] and Air side walls represents the surrounding atmosphere. Air domain is considered as fluid domain and copper wheel is considered as the solid domain rotating at 100 rad/sec. The inner surface of the wheel is water cooled using convective heat transfer. Interface between the air and the solid domain is considered as the coupled interface.

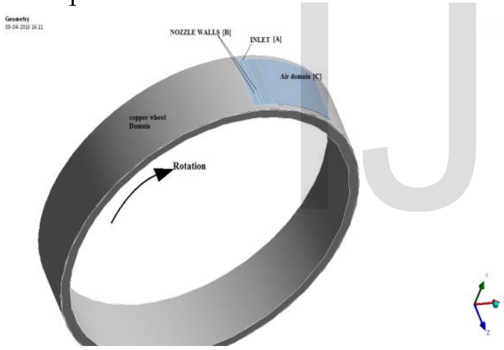


Fig 2a - 3D simulation Domain with boundary

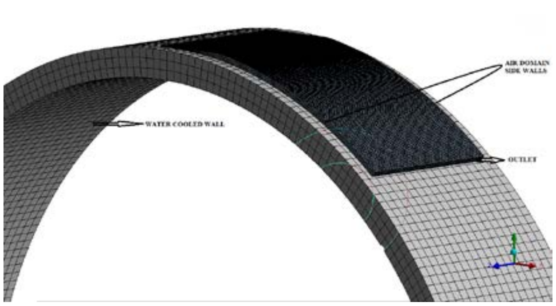


Fig 2b- Mesh domain with boundary conditions.

2.1. Assumptions & Boundary conditions:

In this article, a model that includes the fluid flow with both the free surface and surface tension and the heat transfer with phase transformation in the puddle zone and solid wheel zone is developed.

1. Wheel surface is assumed to be smooth and maintained at a constant temperature.
2. A temperature dependent viscosity to solidify the ribbon to an amorphous state is employed. And flow is laminar
3. All other properties are independent of temperature.
4. No slip condition is assumed at melt wheel and melt nozzle constant so that melt attains the speed of the surface in contact.
5. No heat flux between the nozzle walls and melt (adiabatic). Radiation is neglected from the free surface of the melt.

The governing equations employed based on the assumptions in the CFD modeling technique for understand the ribbon surface quality of the flow originating from the Nozzle slit onto the rotating wheel is given

Continuity equation:

$$D = \frac{\partial U_i}{\partial X_i} = 0 \quad \text{-----------------Eq (1)}$$

Momentum equation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial X_j} = -\frac{1}{\rho}\frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}\left[\nu\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right] + g_i \quad (2) \text{ --- Eq (2)}$$

Volume fraction equation for two phase flow:
Properties in the control volume cell are calculated as below:

$\rho = \rho_m F + \rho_a (1 - F)$

$\mu = \mu_m F + \mu_a (1 - F)$

$C_p = C_{p,m} F + C_{p,a} (1 - F)$

$k = k_m F + k_a (1 - F)$ -------------Eq (3)

Where the suffix 'a' denotes air and 'm' denotes melt and F is the volume fraction of the melt in the cell.
F= 1 for melt and
F= 0 for air.
Where f is the volume force term in the momentum equation resulting from surface tension, given by

$f = (\rho k \nabla F) / [(1/2)(\rho_a + \rho_m)]$ and

k is the curvature and given by

$k = -\nabla[\nabla F / |\nabla F|]$

Energy conservation equation:

$\partial(\rho C_p T)/\partial t + \partial(\rho C_p u_i T)/\partial x_i = (\partial/\partial x_i)(K(\partial T/\partial x_i))$ --- Eq(4)

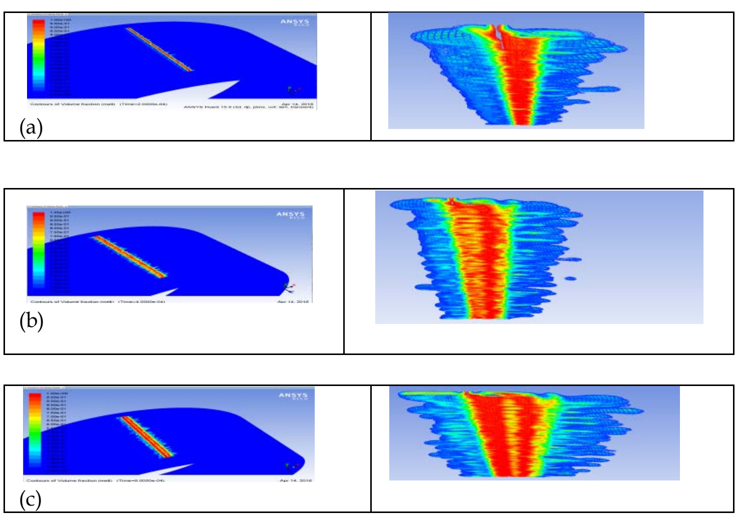
Volume fraction equation:

$(\partial F/\partial t) + u_i (\partial F/\partial x_i) = 0$ ----------- Eq (5)

Temperature dependent viscosity is given by: $\mu_m = 0.10 \times e^{(-3.6528+\frac{734.1}{T-674})}$ -------Eq (6) Heping et al [7]

3.Results And Discussions:

Figure 3 (a to m) shows the Ribbon Formation (Top View) And Puddle shape change (Bottom view) with time sequences. The Molten melt ejects from the nozzle slit and spreads on the wheel surface Fig 3a. The shape approximates the slit boundary and deforms toward the middle of the melt jet under the surface tension and inertial force, as shown the melt touches the surface of the roller and some of the melt is being dragged downstream due to the rotation of the roller Figure 3(b-m). It is speculated by Cox and Steen [2] that the HB Defect is due to the Pinning of the molten metal at USM of the puddle to the nozzle slit. The USM is pinned to the nozzle slit which allows air bubbles to entrain between the puddle and the wheel [8]. The air pockets act as an insulator, reducing the rate of heat-transfer from the puddle to the wheel, locally reducing the ribbon thickness. Thus, the shape of the solidified metal on the wheel side is affected by the physical presence of air pockets[4]. Fig 3c shows that the USM of the puddle is pinned to the nozzle slit and air entrapment is occurring as time progresses. It is also observed that the metal under the nozzle and above the solidification region has no recirculation zone which is correlated with the experimental observations.



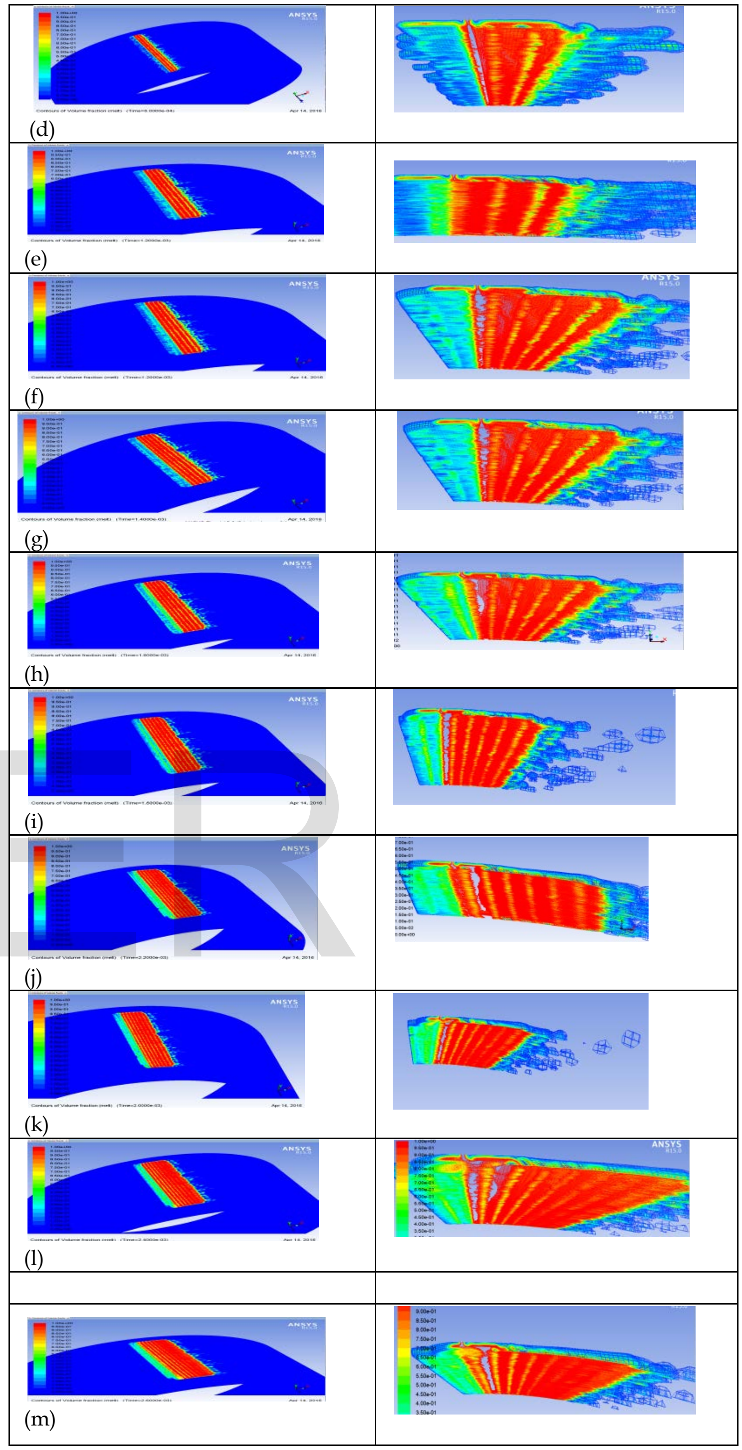


Fig 3: Ribbon Formation (Top View) And Puddle shape change (Bottom view) as a function of time.

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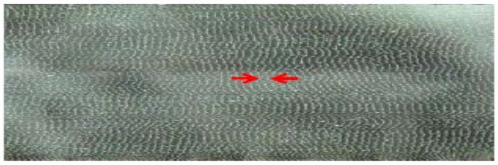

Fig 3.1 a : Photo of Herringbone Defective ribbon

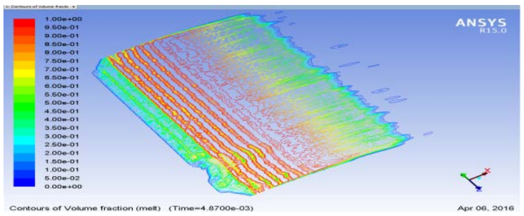

Fig 3.2b: Unfilled VOF contour of Herringbone Defective ribbon formation on the wheel

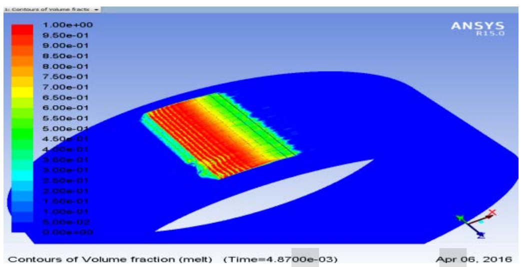

Fig 3.3c: Filled VOF contour of ribbon formation on the wheel

It is observed from fig 3.2 b that the air entraps in the puddle at regular intervals acting as pockets of insulators causing interruption in heat transfer from puddle to the wheel with unsteady fluid motion locally reducing the ribbon thickness. Thus, the shape of the solidified metal on the wheel side is caused by the physical presence of air pockets. The HB defect is appeared with 1 mm spacing.

4. Conclusion:

3D Numerical simulation of PFMS using ANSYS FLUENT observes Pinning of the Upstream Meniscus of the Puddle to the Nozzle slit leading to continuous air ingress which is in agreement with experimental observations. The air entering the puddle acts as an insulator reducing the heat transfer from puddle to the wheel causing reduction in ribbon thickness. Herringbone defect is due to presence of air pocket on the wheel side. Due to pinned condition there is no recirculation of the molten metal in the Puddle region. The puddle length is also less due to the low ejection pressure. Unpinning can be achieved by increasing the ejection pressure.

TABLE 1 PROCESS AND PRODUCT PARAMETERS

Symbol	Typical Value	Description
G	0.0003 m	Nozzle-wheel gap
ω	100 $rad s^{-1}$	Linear wheel speed
W	5 cm	Ribbon width
R	0.30 m	Roller radius
b	0.0006 m	Slit breadth of nozzle
V	1.6 m/s	Velocity inlet
h_w	22987.8 $Wm^{-2} K^{-1}$	Water wall heat-transfer coeff
T_{gp}	873 K	Glass formation tempera Amorphous alloy
σ	1.2 Nm^{-1}	Surface tension
R_d	0.02 m	Copper thickness

TABLE 2: PROPERTIES AND PARAMETERS

Symbol	Typical Value	Description
Fe-B-Si Ribbon		
ϱ	7180	Density, kg/m^3
Cp	544	Specific heat capacity, J/kg – K
T_m	1533	Melt temperature, K (◦C)
μ	Eq [1]	Viscosity
k	8.99	Thermal conductivity , J/m - K - s
Surrounding air		
ϱ	1.225	Density, kg/m^3
Cp	1006.43	Specific heat capacity, J/kg- K
T	300	Temperature, K (◦C)
k	0.0242	Thermal conductivity , J/m -K- s
μ	1.7894 9X 10^{-5}	Viscosity
Cu Wheel		
ϱ	8978	Density, kg/m^3
Cp	381	Specific heat capacity, J/kg – K
k	387.6	Thermal conductivity , J/m - K - s

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