Simulation based Analysis of Junctions in Casting for Reducing Defects: a Review

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Abstract— In investment casting process, many casting defects are occurred due to poor design of part with respect to manufacturability. Some defects cannot be eliminated by changes to tooling and process parameters. Now a day casting defects can be predicted by casting simulation and corrected by modification to part design using casting DFM (design for manufacture) guidelines. The importance of DFM and casting simulation in casting design is well established in casting industry. Sometimes Casting part design is analyses with respect to junctions and corner in casting part. Casing junctions, intersections of two or more sections leading to mass concentration, are potential location of gas porosity and cold shuts.

Key words: Casting, Junctions, Shrinkage Defect, Solidification Simulation, DFM (Design for manufacturability)

I. INTRODUCTION

Junction in a casting design is an abrupt or discontinuous increase in cross-section caused by meeting of two or more elements resulting in regions of high thermal concentration. Molten metal at the junction does not possess sufficient surface area for cooling as compared to the sections; hence junctions solidify at the end and this typically leads to porosity defects if the junctions are not fed properly for volumetric contraction from liquidus to solidus temperature. As the number of sections meeting at junction increase, surface area for cooling further decreases, resulting in more severity of hot spots and hence porosity defects.[8]

ASM (1962) illustrates the potential of shrinkage porosity defect in L, T, V, +, and Y junctions. Minor changes to junction geometry as adding of fillets, changes in geometry of section and use of core are applied to reduce the area of defect. Caine (1963) established relationship between fillet radius, stress concentration and thermal gradients and derived fourteen rules for minimum stress concentration and maximum cast ability for casting shapes varying from a straight junction (abrupt change in cross-section area) to complex junctions as ‘X-T’ junctions. Loper (1976) extended Chvorinov’s modulus approach for determining the sequence of solidification, important for feeder placement close to the last solidifying region. They generated plot depicting solidification sequence for L-junction, T-junction and plus- junctions. They also constructed these charts for varying fillet radius and considering the effect of chills (ASM 1980). [10]

II. CLASSIFICATION OF CASTING JUNCTIONS

A general characterization of junctions with N number of elements (or walls) is proposed here, based on section attributes, section orientation, additional geometric features, and feed ability properties (Figure 2). These are described here.

A. *Section Attributes (For Each Element)*

- L - Length of element
- t - Thickness of element
- h - Height
- r - Fillet radius

B. *Section Orientation (For Each Element)*

- Θ, Φ - Angular references

C. *Additional Geometric Features*

- A - Cross-section area
- H/t - Extent of contact between adjacent elements:
- Cross-section type: (R) rectangular, (C) circular, (O) oval, (FF) freeform
- Central hole (if present): shape, surface area
- Plane orthogonal to junction: Number of such planes and their section properties, offset of such planes from junction and their orientation

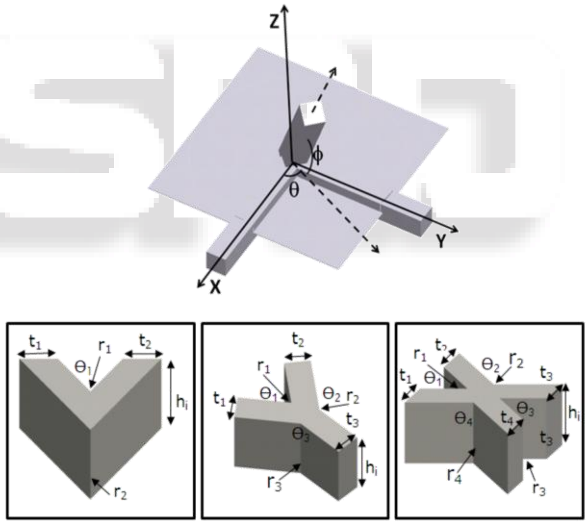

Fig. 1: Junction parameters and types

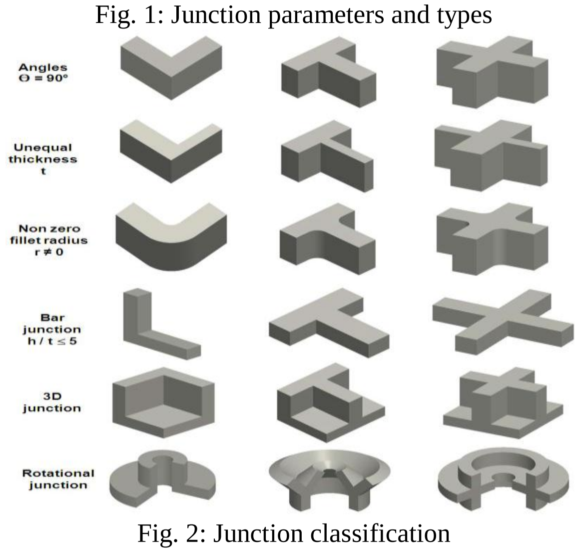

Fig. 2: Junction classification

From the above definition, junctions of two sections ('V' or 'L'), three sections ('Y' or 'T'), and four sections ('X' or 'K') can be derived. Further, two dimensional variations with unequal thickness, unequal and non-orthogonal angles, fillet radius, and bar elements, as well as three dimensional variations with an additional element or with rotational geometry can be derived as shown in Figure 2. [7]

III. VECTOR ELEMENT METHOD

Casting simulation is carried out using the Vector Element Method, which traces the feed metal paths in reverse to pinpoint the location of hot spots (Figure 3). It is based on the principle that the direction of the highest temperature gradient (feed metal path) at any point inside the casting is given by the vector sum of individual thermal flux vectors in all directions around the point. Multiple hot spots, if present, are detected by starting from several seed points.[8]

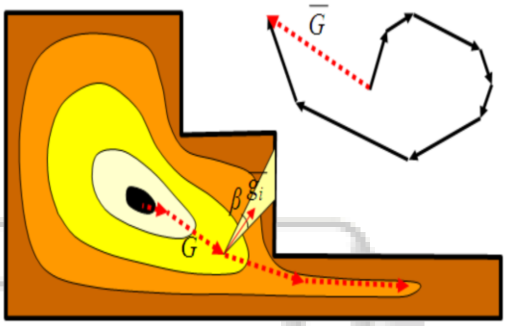

Fig. 3: VEM applied to L-junction

The method is based on determining the feed path passing through any point inside the casting and following the path back to the local hot spot. The feed path is assumed to lie along the maximum thermal gradient. The gradient can be determined from Fourier's law of heat conduction as follows:

q = −K A ΔT Δ s

Equation 1

G= (−1 K) w

Equation 2

Where, G = ΔT / Δs is the thermal gradient and, w = q / A is the heat flux at given point inside the casting, in given direction. The gradient (as well as the heat flux) is zero in a tangential direction to the isotherm passing through the point, and the maximum in perpendicular direction. The magnitude and direction of the maximum thermal gradient at any point inside the casting is proportional to the vector resultant of thermal flux vectors in all directions originating from that point. [8]

IV. INFLUENCE OF JUNCTION PARAMETERS

After establishing the reliability of solidification simulation using VEM, sensitivity analysis is presented here for the influence of individual junction parameters on the hot spot area measured in the junction region. The area of hot spot is the temperature range 1485-1650 °C (2705 - 3002 °F) (Figure 6). To understand the influence of a parameter, other parameters are kept at their nominal values (given below). Parameters considered are: (1) inner radius 'r1' (2) outer radius 'r2' (3) thickness 't' (4) angle 'θ', and (5) length of junction 'L'. These are indicated in Figure 7. Their nominal values are set as

r1=0, r2=0, t=30 mm (1.18 in), θ=0°, and L=240 mm (9.45 in). The height h is set at 30 mm (1.18 in). [11]

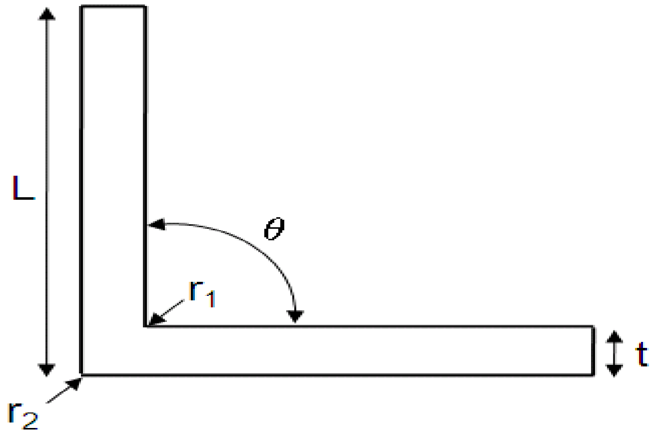

Fig. 4: Parameters of L junction

A. Inner Radius

Inner radius (r1) is varied in steps of 15 mm (0.59 in) as 0, 15 mm (0.59 in), 30 mm (1.18 in), 45 mm (1.77 in) and 60 mm (2.36 in), keeping other parameters at nominal values mentioned above.

B. Outer Radius

Outer radius r2 is varied in steps of 15 mm as 0 mm, 15 mm (0.59 in), 30 mm (1.18 in), 45 mm (1.77 in) and 60 mm (2.36 in), keeping other parameters at nominal values.

C. Thickness

Thickness (t) is varied in steps of 6 mm (0.24 in) as 30 mm (1.18 in), 36 mm (1.42 in), 42 mm (1.65 in), 48 mm (1.89 in), 54 mm (2.13 in) and 60 mm (2.36 in), keeping other parameters at nominal values.

D. Angle

Angle (θ) is varied in steps of 30 degrees as 30°, 60°, 90°, 120° and 150°, keeping other parameters at nominal values.

E. Length

Length (L) is varied as 5 mm (0.20 in), 10 mm (0.39 in), 20 mm (0.79 in), 30 mm (1.18 in), 60 mm (2.36 in), and 90 mm (3.54 in), keeping other parameters at nominal values.[11]

S. No.	Inner Radius 'r_1'	Effectiveness	Outer Radius 'r_2'	Effectiveness	Thickness 't'	Effectiveness	Angle 'θ'	Effectiveness	Length 'L'	Effectiveness
1	0	0.00	0	0.00	30	0.00	30	0.00	5	0.00
2	15	173.08	15	83.21	36	2.93	60	3.38	10	75.13
3	30	158.93	30	39.94	42	3.32	90	3.31	20	42.47
4	45	134.25	45	25.15	48	3.66	120	3.28	30	32.01
5	60	107.76	60	17.47	54	4.78	150	3.25	60	18.71
6	-	-	-	-	60	6.05	-	-	90	12.87

Table 1: Effectiveness of Design Changes

V. DFM GUIDELINES FOR 3D JUNCTIONS

The conclusions of above analyses along with established guidelines can be used in a framework proposed for DFM of 3D junctions. A given junction is first classified to identify the type of junction. Then VEM based solidification simulation is carried out and temperature contours are obtained. The hot spot area is measured and compared against a predefined limit (depending on the desired quality level). If the HSA is more than the set limit, junction DFM rule given in Table 2 are applied to modify the junction design, subject to functional requirements of the part being satisfied. The process is repeated. [3]

No	DFM rule
01	Reduce the number of elements meeting at junction
02	Make thickness uniform for elements
03	Reduce inner fillet radius and inner chamfers
04	Increase interior angles (from acute to 90° or more)
05	Provide outer fillet radius or outer chamfer
06	Reduce the length of elements
07	Place a core at the middle of junction

Table 2: Junction DFM Rules

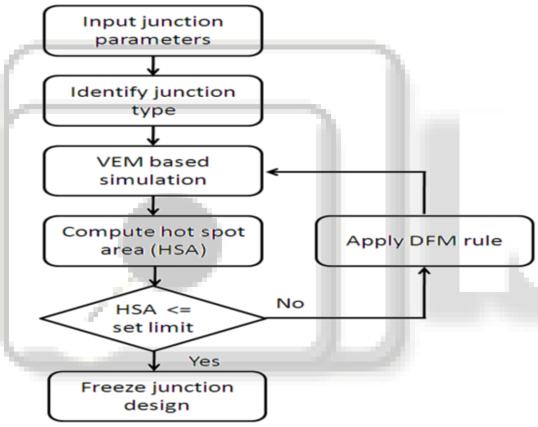

Fig. 5: Junction redesign framework

As an example, consider a 3D box corner junction (Figure 19). The original design consists of three plate elements meeting at a junction. Thicknesses of these elements are 50 mm (2.36 in), 30 mm (1.18 in) and 15 mm (0.59 in). Length of plates for all these elements is 240 mm (9.45 in). The material is aluminium LM-25. Solidification simulation is performed using VEM. [10]

The first revised design of box corner junction has uniform walls of 30mm (1.18 in) leading to over 90% reductions in HSA. This is associated with a volumetric change 14.21%. The effectiveness of this rule is 6.43. For seeking further improvement, three more designs of revised box corner junction are considered. These are: (1) uniform thickness along with a corner chamfer equal to thickness of plate, (2) uniform thickness along with a fillet radius equal to 50% thickness of plate, and (3) uniform thickness along with a fillet radius equal to 75% thickness of plate. These designs and their solidification simulations are shown in Figure 19. Highest effectiveness of 6.77 is obtained with box corner junction design having uniform thickness along with a corner chamfer (equal to the thickness of plate). Hence this design is proposed as the most effective DFM guideline for box corner junction design. [10]

VI. CONCLUSION

A casting can be viewed as an assemblage of junctions mostly of three dimensions. While DFM guidelines have been documented in various sources for 2D junctions, three-dimensional geometrical variations of junction have been largely ignored. A junction by its geometric nature is a region of high thermal concentration. Geometrical variations of junction influence the potential and location of this high thermal concentration. The proposed classification of junctions in two and three dimensions helps in identifying the location of this high thermal concentration region and its influence on shrinkage porosity defects. In this paper casting simulation using vector element method has been validated by experimental results. The simulation results are then applied to evaluate four possible design alternatives for the 3D box corner junction. The design with constant outer fillet radius appears to be the most promising DFM guideline for box corner junction. Similar DFM guidelines can be prepared for other 3D junctions to minimize the porosity problems in cast products or to design a suitable feeder to feed the junctions in a more effective manner.

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