

## 3D Junctions in Castings: Simulation-based DFM Analysis and Guidelines

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### ABSTRACT

Many casting defects, which cannot be eliminated by changes to tooling and process parameters, can be attributed to poor design of the part with respect to manufacturability. One such common defect is shrinkage porosity at casting junctions. The defects can be predicted by casting solidification simulation, and corrected by minor modification to part design. However, most design engineers do not have sufficient experience in casting to run the simulation programs and interpret the results properly. To overcome this problem, we present a scientific classification and analysis of casting junctions, and part design guidelines derived from simulation. The junctions are first classified as 2D and 3D, bar and plate type. The junction parameters include number of converging elements, cross-section of sections, angle between pairs of elements, and thickness of the junction. The junctions include L/V, T/Y and X/K, without or with additional elements normal to the plane of primary elements. The junctions have been solid modeled, and subjected to solidification simulation to predict the location of shrinkage defect. This was validated by casting the junctions in aluminum-alloy and steel to observe the location of actual defects, and calibrate the simulation model. Geometrical variations in junction design were analyzed to study the effect on defect location and extent. Based on this, design guidelines indicating the best values and ratios of junction parameters were evolved. A case study of box corner junction is presented in this paper.

**Key Words:** Casting, Junctions, Shrinkage Defect, Solidification Simulation.

### 1. CASTING JUNCTIONS

*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.

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 castability 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). Experimental analysis of solidification wave front conducted by Kim, et al., (1985) included a series of castings with V-junctions by decanting the liquid at various stages of solidification. It showed that higher the outside and inside angle of V-junction, greater is the progress in solidification front. The same is true for higher values of inner and outside fillet radius. Design guidelines for simple two-dimensional junctions including L, T, V, Y and Plus are presented in Bralla 1990 and Ravi 2005. These guidelines suggest minor changes in junction geometries to reduce the potential for porosity defect.

The work reported so far is predominantly in two-dimensional domain, where as in real life castings junctions are in 3D and with more complexity. In this paper, we present a generic classification of junctions followed by simulation based on vector element method (Ravi, 1996, Ravi, 1990). Experiments are conducted in Aluminum (LM25) and Cast steel (0.2% C) to compared the simulated and actual porosity defects, and to study the effect of geometric parameters of junction. Figure 1 shows 3D box corner junction in Aluminum (LM 25) of size 240 mm thickness 30 mm, made using sand casting process. Concentrated porosity defect is observed at the junction area.

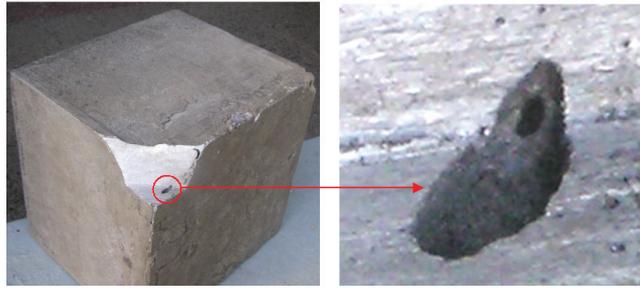


Figure 1: Concentrated porosity defect in 3D box corner junction, material LM-25

## 2. JUNCTION CLASSIFICATION

Junction classification can be geometrically represented in two dimensions (figure 2) or three dimensions (figure 3). The geometrical variation presented in these figures affects the thermal modulus and thereby heat concentration at the junction area. In these figures, thickness, fillet radius, height, and angle are denoted by  $t$ ,  $r$ ,  $h$  and  $\theta$  respectively.

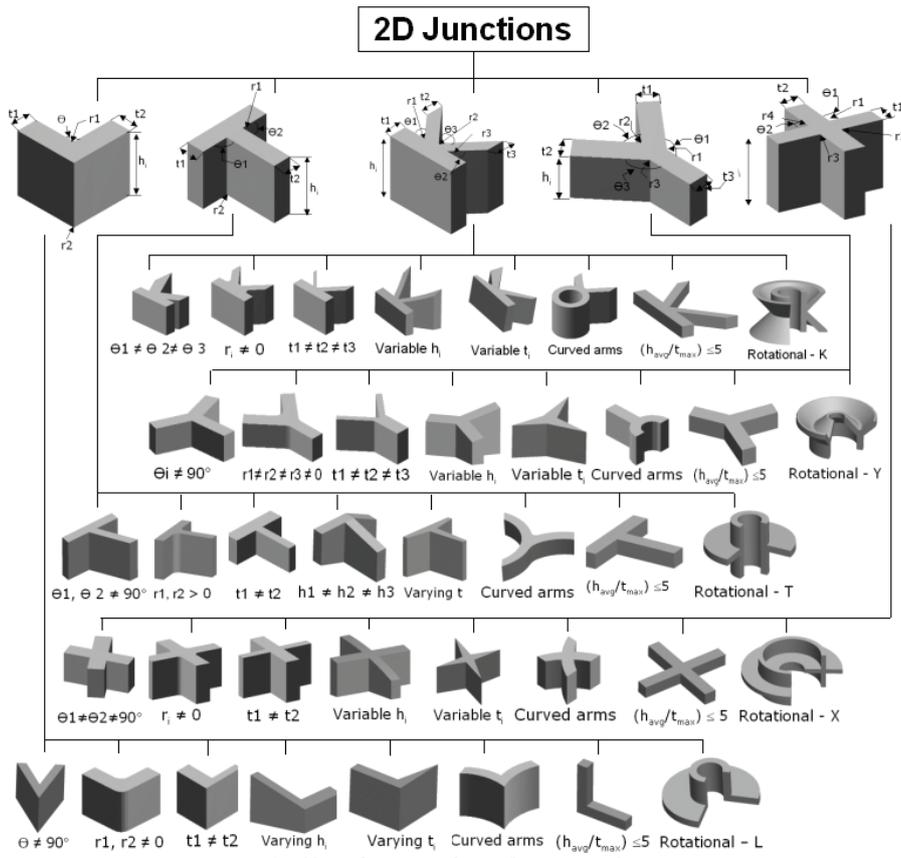


Figure 2: Classification of two-dimensional junctions

# 3D Junctions

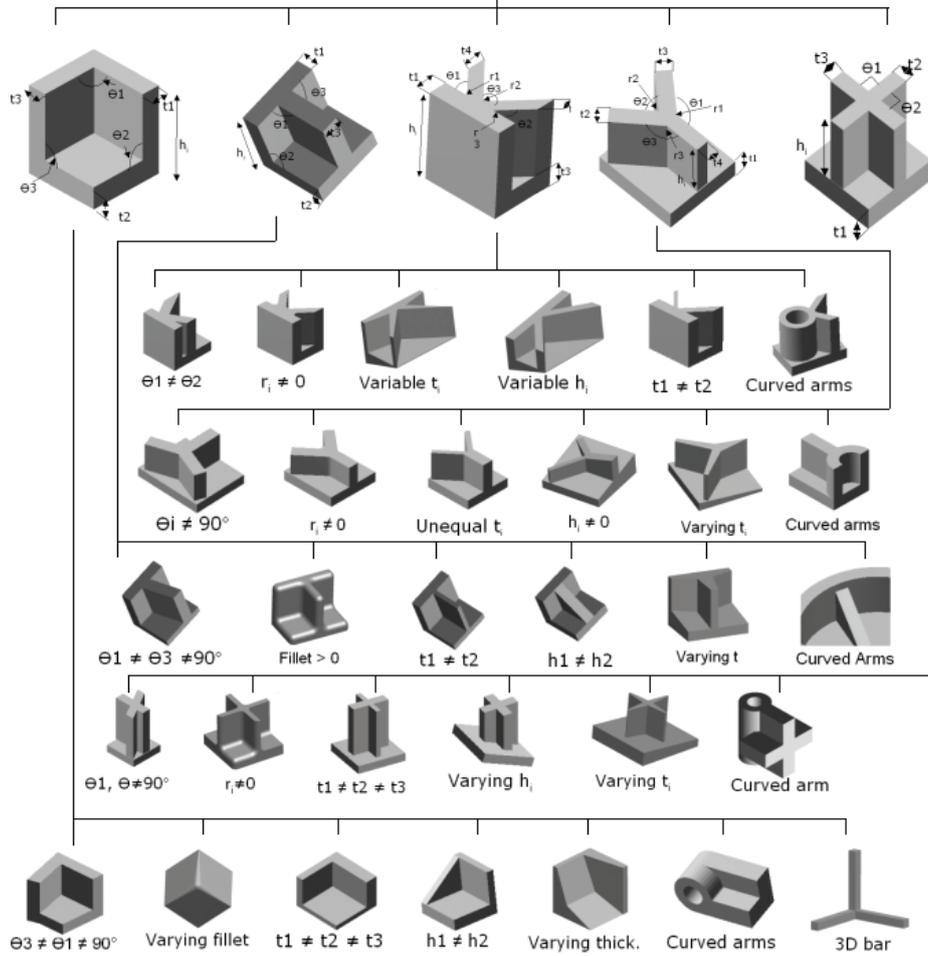


Figure 3: Classification of three-dimensional junctions

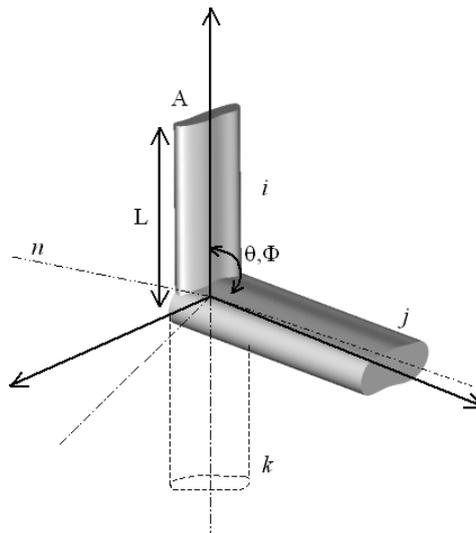


Figure 4: Various parameters of a junction

A general characterisation of junctions with  $N$  elements (1, 2, 3, ...  $N$ ) can be made on the basis of section attributes, section orientation, additional geometric features, and feedability properties (figure 4). These are briefly described here.

**(a) Section attributes – for each element**

- Type of cross-section: rectangular, circular, oval, free form

- Extent of contact between adjacent sections: plate or bar junction
- Average cross-sectional area:  $A$
- Length of section:  $L$
- Minimum, maximum and average thickness:  $T_{min}$ ,  $T_{max}$ ,  $T_{avg}$
- Surface area: maximum, minimum, average (over the length of sections)
- Volume: maximum, minimum, average (over the length of sections)
- Section Type: reference or general
- Type of fillet on either side: constant, varying

**(b) Section orientation – for each element**

- Angular references:  $\theta$ ,  $\Phi$ , for reference plane  $\theta$ ,  $\Phi=0$

**(c) Additional geometric features**

- Central core: present or absent, volume, surface area
- Presence of plane orthogonal to junction,
- No of such planes and their section properties,
- Offset of such planes from junction,
- Orientation of such planes

**(d) Feedability properties**

- Location with respect to feeder
- Location with respect to in-gate

### 3. SIMULATION USING VECTOR ELEMENT METHOD

Casting simulation is carried out using AutoCAST software program ([www.autocast.co.in](http://www.autocast.co.in)). In this software casting solidification is simulated using the *Vector Element Method*, which traces the feed metal paths in reverse to pinpoint the location of hot spots. 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 (Ravi 2005). Multiple hot spots, if present, are detected by starting from several seed points. L-junctions with the following parameters were simulated for solidification simulation:

- (1) L-90-30-30-240-240-0-0
- (2) L-90-30-30-240-240-0-30
- (3) L-90-30-30-240-240-5-15
- (4) L-90-30-30-240-240-30-50

Here, L: type of junction, 90: angle between the element, 30: thickness 1, 30: thickness 2, 240: element length 1, 240: element length 2, 0: inner fillet and 0: outer fillet.

The progressive solidification simulation results are shown in figure 5 clockwise from top. Draw brown (dark) regions show the solidified portion of the casting and yellow, bright yellow (light) regions belong to higher temperature that will subsequently solidify. The white region represents the hot spot, which is the region with the highest temperature. Molten metal in this hot spot region feeds the surrounding regions (for solidification contraction) as the surrounding regions solidify. If this hot spot region is not fed by liquid metal from feeder, it will eventually result into porosity defects. For case (1) that is L junction with sharp corners substantial region of hot spot is observed this hot spot region increases in size when outer fillet is provided (case 2) this is because thermal concentration further increases. In case 3, fillet radius is provided on both inner and outer sides, but they seem to be insufficient to control the potential of hot spot. Providing fillet radius of 30 mm on inner side and of 50mm on outer side (case 4) makes the L- junction of uniform thickness and this reduces the region of hot spot.

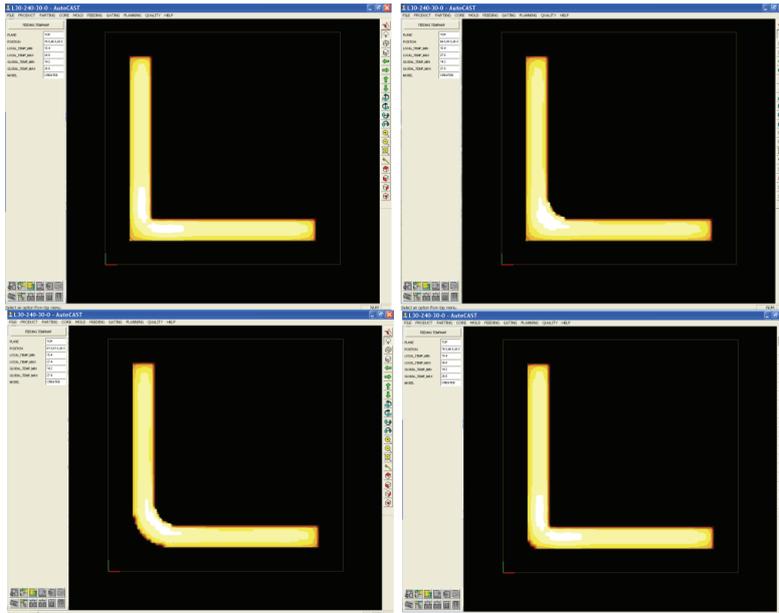


Figure 5: Solidification simulation of L-junction with variations in geometry

#### 4. EXPERIMENTAL VALIDATION

Experimental casting of L-junctions was done in Cast Steel (0.2% C) with four variations in junction design mentioned earlier (fig. 6). Conventional green sand casting process was used with pouring temperature 1630 C. Radiography tests were performed on these castings and the amount of area was measured with the help of AutoCAD software (fig. 7). It is observed from the radiography test that L-junction with sharp corners results in porosity defect of 88mm<sup>2</sup>, with a crack (case 1). L-junction with 30 mm inner radius and 0 mm outer radius results in a defect area of 123mm<sup>2</sup> (case 2), with fillet radius of 5mm (inner) and 15mm (outer), the defect area got reduced to 61mm<sup>2</sup> (case 3). The concentrated porosity defect was reduced to centerline porosity with fillet radius of 30mm (inner) and 50mm (outer). The porosity defect was reduced to 42mm<sup>2</sup> (case 4).



Figure 6: L-Junction experimental casting in Cast Steel



Figure 7: Radiography results of L-Junction casting in Cast Steel

The location of defect as obtained in all the four cases are matching with that obtained by solidification simulation (fig. 5). The potential of defect as demonstrated by the solidification simulation has been observed in the radiography tests. This experiment also confirms that minor changes in junction geometry can help in minimizing the amount of porosity defect.

## 5. DESIGN FOR MANUFACTURE GUIDELINES FOR 3D JUNCTIONS

The benchmarking experiment comparing solidification simulation with experimental results validates the use of simulation for generating design guidelines for other junctions. In this section, Design for Manufacture (DFM) guidelines for 3D box corner junction are presented.

The solidification simulation was performed for 3D Box corner junction with sharp edges (referred to as original design). The solidification contours through the center of the section are shown in figure 8. White regions denoting hot spots are present in the center of the progressive solidification contour.

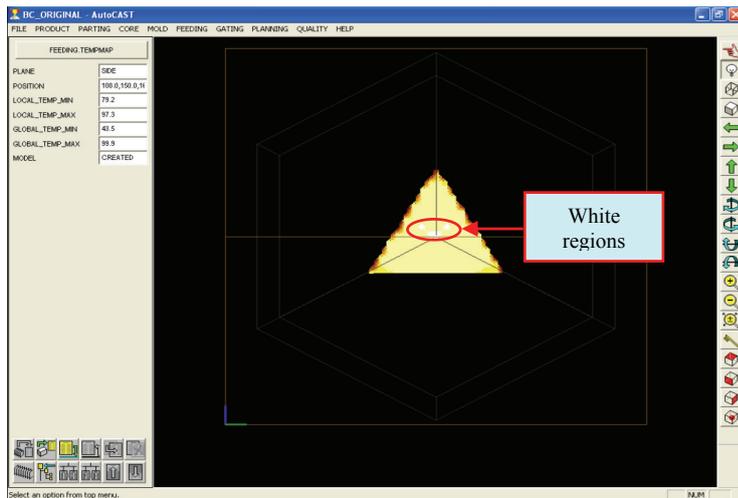


Figure 8: Progressive solidification contours for original box corner junction.

Due to high thermal concentration in the junction area, the hot spots eventually end up as porosity defect (fig. 1). The design changes presented in figure 9 are the possible suggestions to reduce the thermal concentration. Solidification simulation is again performed on each of these design changes and the progressive solidification contours are presented in figure 10.

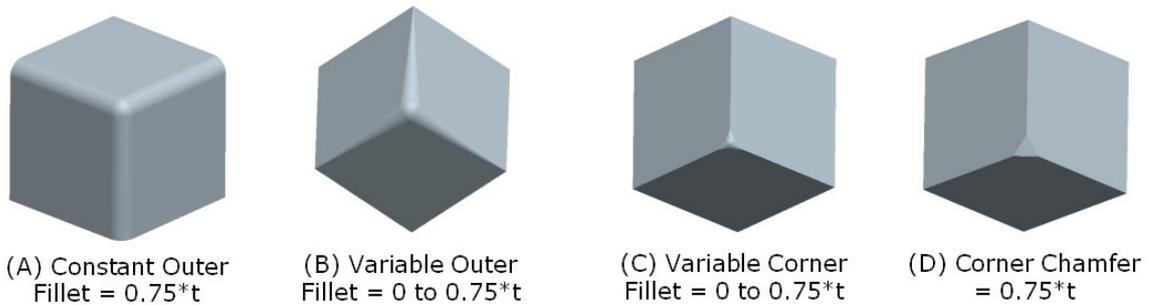
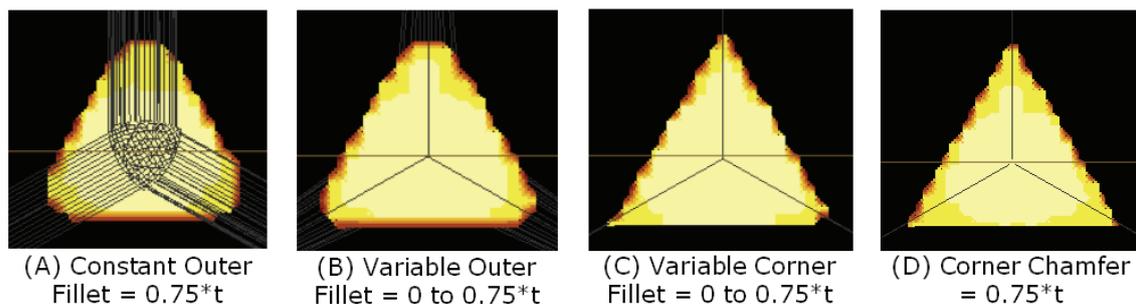


Figure 9: Design modification suggested for box corner junction.

Figure 10: Progressive solidification contours for the four design modifications.



It has been observed that each of the progressive solidification contours is free from white spots that were present in the original design. Bright yellow area of the progressive solidification simulation represents the temperature range, which is 10% lower than that of hot spot temperature range. Eliminating white regions minimizes the possibility of concentrated porosity defect, while minimizing the bright yellow area minimizes the possibility of micro porosity (in case junctions are not adequately fed by the feeder). This area is the largest for the design with variable corner fillet radius, and is lower for designs in following order (1) variable outer fillet radius (2) corner fillet and (3) constant outer fillet radius. The design with corner chamfer may result in a weaker junction and variable outer radius is difficult to manufacture and hence these design suggestions cannot be the possible DFM guidelines. The design with constant outer fillet radius has minimum bright yellow area this design modification appears to be the most promising DFM guideline of box corner junction.

## 6. 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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