ABSTRACT

Feeding or risering system of a casting significantly affects the internal quality as well as the yield of a casting. It is however, quite difficult to predict the effect of a particular set of feeder design parameters (such as location, shape and dimensions) on casting quality. Hence feeding system design is iterative in practice, involving tooling modification, foundry trials and inspection. Computer simulation can save material and production resources involved in foundry trials, but requires a higher level of human effort for preparing the inputs and interpreting the results properly.

In this work, we have evolved a new approach to evaluate and optimize casting feeding system design using feed-paths. The feed-paths are computed by Vector Element Method (VEM). It is possible to automatically track the direction of the feed metal flow from a given point, and to check if a feeder is effective. The convergence of the feed-paths provides a clear indication of directional solidification and location of shrinkage defects. Further, this takes a fraction of the time taken by FEM-based simulation, making it more useful for practical application. The proposed approach is demonstrated by automatically optimizing the feeder size for a benchmark casting, and validated by pouring and sectioning Al-alloy castings made in sand molds.

Key Words: Feeding system, Feed-paths, Solidification simulation, Shrinkage defects.

INTRODUCTION

The volumetric contraction of molten metal during solidification (1-5%) is compensated by liquid metal moving from adjacent hotter region to the solidifying region. The direction of this microscopic flow of metal is referred to as feed-path. If the feed-paths converge inside a feeder, it implies proper feeding of the casting. If they converge at some point inside the part, then this region will form a local hot spot and results in shrinkage defects such as cavity, porosity, centerline porosity, or sink depending on the cast and mold materials. In such cases, feeding system needs to be revised, to ensure adequate feed metal to the part by directional solidification. Minimizing the number of feeders (to reduce fettling cost), and the total volume of feeders (to reduce melting cost and improve productivity) are also important considerations.

Various parameters of feeding system are shown in Fig. 1. Feeding system design is iterative in practice, with repeated cycles of tooling modification, shop floor trials and inspection. These production resources can be saved by computer-aided design of casting (with feeders) and solidification simulation. The conventional as well as computational approaches for feeder optimization have their own limitations, as seen from the literature review presented in the next section. A fast and reliable approach for feeder optimization is presented in this paper, based on the concept of feed-paths, which are automatically generated using the Vector Element Method.
LITERATURE REVIEW

In practice, feeders are designed using the modulus method, which involves subdividing the part into simple shapes and computing the ratio of volume and cooling surface area (referred to as modulus). The sub-division with the highest modulus is considered to solidify last, as per the Chvorinov's equation [1]. A feeder with an even higher modulus is attached to the region to ensure adequate feeding [2]. Sub-dividing a complex casting is however, subjective and difficult, and usually leads to an undersized feeder. This approach cannot account for non-uniform cooling from curved surfaces, cored features and feedaids, which are common in industrial castings [3]. Availability of sufficient feed metal volume is checked by the equation $e V_f = a (V_f + V_c)$, where $e$ is the feeder efficiency, $a$ is solidification shrinkage, $V_c$ is casting volume, and $V_f$ is feeder volume. This equation usually overestimates the feeder volume, as evident from the shrinkage depth of feeder (pipe) [4].

The above limitations can be overcome by computer simulation of casting solidification for feeder evaluation and optimization. The mathematical model of heat transfer during casting solidification is solved using computational techniques such as Finite Element, Finite Difference, and Boundary Element Method [5-7]. The results include the temperature values at different locations in the casting at different instants of time as the casting cools from its pouring temperature. Temperature gradients and cooling rate can be computed subsequently. These results help in visualizing and interpreting the progress of solidification front and time. Lewis [8] demonstrated the use of FEM for optimization of feeder shape and volume of a hub casting. They investigated several geometric variants within allowable constraints using FEM and finalized the design with considerable reduction in size of feeder. Kuyucak [9] compared feeding rules for steel casting as documented by Steel Founders’ Society of America [10] and suggested corrections based on Niyama criterion and their simulation studies.

The numerical simulation techniques are based on manipulations of huge matrices and iterative calculations, making them computationally intensive [11]. For complex-shaped parts, computer simulation can take several hours [12]. Many critical inputs, including temperature-dependent material properties and interfacial heat transfer coefficients are difficult to expect from foundry engineers. Owing to a large number of feeder design parameters, multiple simulation runs are needed, often taking several days. Further, simulation results are usually difficult to interpret. These limitations severely constrain the application of computer simulation in actual practice.

The Vector Element Method (VEM) proposed by Ravi and Srinivasan [13, 14] provides a fast and reliable approach to casting solidification simulation with minimal user inputs [15, 16]. This method relies on tracing the feed-paths from any given point inside the casting to the nearest hot spot. Several industrial case studies illustrating the application of VEM to casting quality improvement are available [17, 18].

In this work, we propose a novel methodology for automatic evaluation and optimization of feeders based on the interpretation of feed-paths. Feed-paths are usually generated from the part boundary to visualize the direction of solidification (from early freezing regions to later freezing regions). The point of convergence of the feed-paths is checked to ensure it is inside the feeder, implying adequate feeding. Otherwise, the feeder dimensions are modified, and feed-paths are generated again. To further reduce the computation time in feeder design iterations during optimization, the feed-paths are generated only from the part hot spot.

![FIGURE 1: FEEDING SYSTEM PARAMETERS](image-url)
COMPUTATION OF FEED-PATHS

In Vector Element Method, the casting geometry is divided into a number of segments from a given point and the modulus vector is computed for each geometric segment. The length of the vector is given by the ratio of volume to heat transfer surface area of each segment [19]. The resultant of these vectors gives the feed-path at that point. The computation can be repeated at the new point along the feed-path, eventually leading to the local hot spot. Multiple feed-paths can be generated from starting from different points along the boundary of the cast part. The convergence point and profile of these feed-paths provides a clear insight regarding the direction of solidification and occurrence of shrinkage related defects.

The methodology is illustrated with a ‘L’ shaped casting shown in Fig. 2a. Consider a point \( P_i \) near the part boundary. Divide the part around the point, with equal segment angle, \( \beta \). Here a large segment angle (45°) is shown to illustrate the concept, so that the number of segments, \( n \) are only eight. For each segment, modulus vector, \( \vec{M} \) is computed using Eq. (1) and plotted with dotted arrows. \( V_i \) is the volume and \( A_i \) is heat transfer surface area of the geometric segment, \( i \). Their vector sum represents the direction of the adjacent point with the highest modulus as shown by the thick arrow. A pre-defined step is taken along this direction to obtain the next iteration point \( P_{i+1} \).

\[
\vec{M} = \frac{V_i}{A_i} \quad (1)
\]

The procedure is repeated at point \( P_{i+1} \) and continued till it reaches a location where the resultant modulus vector is below a pre-defined lower limit. This last point \( P_{i+m} \) indicates the local maxima of temperature (hot spot), where temperature gradient tends to be zero. The locus of the points during the iteration from \( P_i \) to \( P_{i+m} \) represents the feed-path. During solidification, when temperature \( T_i \) of the molten metal at point \( P_i \) reaches the solidus temperature, feed metal is supplied from point \( P_{i+1} \) to compensate solidification shrinkage. Computation of multiple feed-paths starting from various points along the part boundary is shown in Fig. 2b. They all converge to the local hot spot.

Multiple hot spots, if present, are automatically discovered by separate points of convergence of the feed-paths. Boundary conditions like cores, chills, insulating/ exothermic sleeves and covers are handled by using a boundary factor, \( f_b \) which is a similar to the Modulus Extension Factor (MEF) used to define feedaids. Boundary factor is applied to each geometric segment as indicated by Eq. (2).

\[
\vec{M} = f_b \frac{V_i}{A_i} \quad (2)
\]

Where, \( f_b = f \) (MEF)

A benchmark part with multiple junctions is designed to illustrate the methodology for feeding system evaluation and optimization (Fig. 3a). Feed-paths are first computed for this part without any feeder as shown in Fig. 3b. The feed-paths converge at (130, 65) mm coordinates and indicate a hot spot inside the heavy boss. To corroborate the results, a FEM-based solver, ProCAST is employed to generate temperature results,
which also indicate the hot spot at the same location as shown in Fig. 3c. Finally, the casting is produced by pouring LM6 alloy at 710 °C in a sand mold. The cut section of the casting shows a shrinkage cavity (Fig. 3d), whole location clearly matches the computed results (feed-path convergence, as well as hot spot). The computations were performed on a 32-bit Windows XP computer equipped with 2.6 GHz processor and 4 GB RAM. The FEM results took about 140 minutes (excluding pre and post-processing) for a mesh size of 1 mm. The VEM results took less than 10 minutes with the same mesh size.

**FIGURE 3:** (a) BENCHMARK PART, (b) FEED-PATHS USING VEM, (c) TEMPERATURE CONTOURS USING FEM, (d) CASTING SECTION SHOWING SHRINKAGE DEFECT

**OPTIMIZATION OF CASTING FEEDING SYSTEM**

Optimization of feeding system involves achieving the desired internal quality (free of shrinkage defects) at the lowest cost. The quality is ensured by feed-paths converging inside the feeder. A smaller feeder gives higher yield, which implies lower melting cost and higher productivity. The exercise is initiated by connecting a sub-optimal size feeder to the casting and computing the feed-path from the hot spot in the casting. If this feed-path reaches inside the feeder, then the feeder is considered effective. If the feed-path stops inside the part itself, then the feeder is enlarged and feed-path computed again (Fig. 4). This is continued until the feed-path moves into the feeder.

![Diagram of feeding system optimization](image)

**FIGURE 4:** METHODOLOGY OF FEEDING SYSTEM OPTIMIZATION

The above methodology is applied to the benchmark part. A cylindrical top feeder is designed using Chvorinov’s equation. This has a diameter of 60 mm and height of 80 mm; the neck is designed with a diameter of 35 mm and length of 10 mm. The feed-paths computed for this part (as shown in Fig. 5a) converge inside the part, as well as feeder neck and the feeder. In other words, a chain of hot spots are observed along the centerline of the feeder and extend into the part. The inadequate feeder size is confirmed by the temperature distribution and solid fraction results generated by FEM (Fig. 5c and 5d). The experimental castings with the above feeder design were produced as before, in LM6 alloy using sand casting process. The cut section shows shrinkage defect matching the VEM and FEM results (Fig. 5b).
For optimizing the feeder design, iterations are performed by changing the feeding size in steps, maintaining the same aspect ratio (height / diameter). The modified feeder diameter is given by

\[ D_n = D_{\text{init}} + n\Delta D, \text{ till } D_n < D_{\text{max}} \]

where, \( D_{\text{init}} \) is initial feeder diameter, \( \Delta D \) is the increment step size, \( n \) is the number of iteration and \( D_{\text{max}} \) is the maximum permissible limit of feeder diameter. This limit is driven by either minimum yield criteria (say, 50% for this casting) or some geometric or connection constraints of part.

Considering \( \Delta D = 5 \text{ mm} \), \( D_{\text{init}} = 60 \text{ mm} \) and \( D_{\text{max}} = 90 \text{ mm} \) (considering lowest permissible yield as 50%), the feeder dimensions for the second iteration will be \( D_1 = 65 \text{ mm} \) and \( L_1 = 87 \text{ mm} \). In all, six iterations with feeder diameter 60, 65, 70, 75, 80 and 85 mm are performed. In each iteration, feed-path is computed from part hot spot at coordinates (130, 65) mm and tracked till it stops, as shown in Fig 6. The length of the feed-path from part hot spot to the stopping point is computed in each case.

**FIGURE 5:** BENCHMARK CASTING WITH DIAMETER 60 mm, HEIGHT 80 mm, (a) FEED-PATHS USING VEM, (b) CUT SECTION SHOWING SHRINKAGE DEFECT, (c) TEMPERATURE CONTOURS USING FEM, (d) SOLID FRACTION USING FEM
FIGURE 6: FEED-PATH STARTS FROM PART HOT SPOT DURING SIX ITERATIONS
In the first three cases corresponding to feeder sizes 60 mm, 65 mm and 70 mm diameter, the feed-path stops inside the part itself, indicating shrinkage defect. In the case of 75 mm diameter feeder, the feed-path stops inside the feeder just above the neck. Increasing the feeder diameter to 80 mm pushes the feed-path higher up inside the feeder. The feeder diameter of 85 mm results in a feed-path almost reaching the feeder center.

Considering the length of feed-path stopping at feeder center as the reference, we define feed-path length ratio (FLR) as the ratio of feed-path length for a given feeder with the reference feed-path length. The FLR should be higher than a critical limit (about 48% in this case) to ensure it ends inside the feeder. A higher FLR however, leads to lower yield.

The FLR and yield for the six feeder designs are presented in Table 1 and Fig. 7. The feeder diameter of 75 mm giving a FLR of 64% and yield 62% satisfies both FLR and yield limit constraints, and appears to be the optimal design. The feeder diameter of 80 mm giving a higher FLR of 89% can be recommended as a safer option, though with the penalty of a lower yield of 57%.

The feed-paths for the above feeder with 80 mm diameter are shown in Fig. 8a. All of them converge inside the feeder, indicating a defect-free casting. This is confirmed by the temperature distribution result generated by FEM (Fig. 8b). The actual casting with the above feeder also shows no internal shrinkage defects (Fig. 8c).

**TABLE 1: FLR AND YIELD DURING OPTIMIZATION CYCLE**

<table>
<thead>
<tr>
<th>Feeder dia (mm)</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
<th>85</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLR %</td>
<td>17</td>
<td>26</td>
<td>43</td>
<td>64</td>
<td>89</td>
<td>100</td>
</tr>
<tr>
<td>Yield %</td>
<td>76</td>
<td>71</td>
<td>66</td>
<td>62</td>
<td>57</td>
<td>52</td>
</tr>
</tbody>
</table>

**FIGURE 8: BENCHMARK CASTING WITH DIAMETER 80 mm, HEIGHT 105 mm**
(a) FEED-PATHS USING VEM, (b) TEMPERATURE CONTOURS USING FEM, (c) CASTING WITH SHRINKAGE DEFECT
INDUSTRIAL CASE STUDY

An aluminum-alloy lug casting (Fig. 9a) of overall size 185 mm x 80 mm x 140 mm weighing 2.5 kg produced in a non-ferrous foundry is taken as a case study for demonstrating the overall methodology. The original feeding system includes two conical feeders with top diameter 75 mm, bottom diameter 45 mm and height 70 mm. After fettling and machining the top faces, the casting exhibited a small shrinkage cavity just below the riser as shown in Fig. 9b.

The feed-paths generated using VEM clearly indicate convergence just below the top face of the casting as shown in Fig. 10a, matching the location of shrinkage defect found in the actual casting. The feeder size is inadequate to supply feed metal inside the part during solidification.

As a first step feed-paths are computed for only the part (without feeding system) to identify the part hot spot (where feed-paths converge) as shown in Fig. 10b. Coordinates of the hot spot are (27, 92) mm. Then the feeder is optimized using the methodology described in the previous section. The bottom diameter of the feeder is increased in steps of 4 mm, maintaining the same aspect ratio and taper. Considering minimum yield of 50%, \( D_{max} = 61 \text{ mm} \). Four iterations are performed with bottom feeder diameters of 45, 49, 53, 57 mm. In each iteration, feed-path is generated from part hot spot and tracked till it stops, as shown in Fig. 11a, 11b, 11c and 11d. The length of feed-path from part hot spot is computed in each case.

In cases corresponding to bottom feeder diameter 45 and 49 mm diameter, feed-path stops inside the part and neck region respectively, leading to shrinkage defect inside the part. In case of 53 mm bottom diameter feeder, it stops inside the feeder. When the feeder bottom diameter is increased to 57 mm, the feed-path stops near the geometric center of feeder, which is used for computing the feed-path length ratio. The FLR and yield are presented in Table 2 and Fig. 12. The feeder with bottom diameter of 53 mm gives 80% of the ideal feed-path with a yield of 58%, which appears to be the optimal solution. Figure 13 shows the complete feed-path result for 53 mm feeder bottom diameter. It is clear that hot spot is entirely inside the feeder, ensuring no shrinkage defect inside the part.

![FIGURE 9: (a) LUG CASTING, (b) CASTING WITH SHRINKAGE DEFECT](image)

![FIGURE 10: FEED-PATHS IN (a) PART WITH FEEDER BOTTOM DIAMETER 45 mm, (b) PART WITHOUT FEEDER](image)

CONCLUSION

This work overcomes two major limitations of casting solidification simulation using traditional Finite Element Method. One is that the temperature profiles generated by FEM only indicate the location of hot spots inside the casting, not the direction of feeding of molten metal, which is needed to assess feeder designs. Secondly, FEM based casting simulation is computation-intensive, making it difficult to use it for rapid and automatic optimization of feeder designs.

Feed-paths, which generally lie along the direction of the highest temperature gradients, provide a convenient and reliable visualization of directional solidification inside a casting, enabling automatic assessment of feeder design. The feed-paths can be rapidly generated using Vector Element Method, and can be easily interpreted in terms of convergence and stopping location. Using this approach, we have demonstrated how feeder design can be optimized to achieve a casting free of internal shrinkage defects, while ensuring a high yield. The benchmarking of VEM results in terms of hot spot locations matched those obtained by FEM, and this was further validated by the location of shrinkage defect observed in experimental castings. The VEM took less than 10% of the computation time required by FEM.

In practice, the final design can be verified once using FEM-based casting simulation, if needed, before implementing on foundry shop-floor. The hybrid approach, in which initial iterations are performed by VEM and a final confirmatory...
simulation performed by FEM, takes a fraction of the time taken by feeder optimization using only FEM-based techniques. The present study focused on only feeder size. This can be extended to include other parameters of the feeder, including shape, aspect ratio, taper, neck design, and feedaids.

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