Simulation of Shrinkage Defect Formation in Exhaust Manifold Castings

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This paper investigates the formation of shrinkage defects in exhaust manifold castings via CAE simulation. The JMatPro software is used to calculate the material property data required by the casting simulation package AnyCasting. The effect of alloying contents on materials properties and the subsequent influence on casting behaviour are investigated through computer simulation of feedability and fluidity tests and prediction of the shrinkage defect formation in manifold castings.

Keywords: material data, shrinkage defect, casting simulation, cast irons, exhaust manifold, castability.

1. Introduction

With increasing complexity in casting geometry and continued stringent requirements for completely sound castings, understanding the shrinkage behaviour of alloy castings via CAE simulation is crucial for successful foundry operations. Reliable casting simulation requires accurate material data during solidification, the lack of which has been a common problem for CAE modellers, primarily due to the fact that the traditional way of obtaining such data via experimentation is expensive and time-consuming. While experimental testing remains irreplaceable for the time to come, using the computer software JMatPro to calculate such material data has gradually become a popular alternative [1,2,3,4,5].

The automotive industry has been constantly pushing the operating temperature of exhaust manifolds to go higher and higher, and now it reaches 850°C in diesel engines and over 1000°C in gasoline engines [6]. A direct consequence of this is the constant search for new exhaust materials [7]. Material selection is by no means an easy process. There are lots of requirements to be met by manifold materials, such as oxidation resistance, structure stability, high temperature strength and resistance to thermal cycling [8]. Being able to calculate materials physical and mechanical properties based on alloy chemistry and processing [9,10], JMatPro presents itself as an attractive tool in, at least, the early stages of alloy selection and process design.

This paper studies the propensity to shrinkage defect formation during casting when new exhaust materials are considered. Casting simulation was carried out using the commercial package AnyCasting [11]. Three alloys were chosen as candidate materials for exhaust manifold. JMatPro was employed to calculate the materials properties during solidification of these alloys based on alloy chemistry. The castability of the alloys is evaluated through computer simulated tests of feedability and fluidity. The formation of shrinkage defects during casting of the three alloys is predicted.

2. Materials and Simulation Setup

The compositions of the three alloys used in this study are given in Table 1. Each alloy is of a different matrix type, pearlitic, ferritic, or austenitic. To test the castability of the three alloys, two virtual experiments were carried out; one is a feedability test and the other is the spiral type test of fluidity. The simulation setups of these two tests are shown in Figs. 1 and 2, respectively. The production of exhaust manifolds is via sand casting and its setup is shown in Fig. 3. The pouring temperature is 1400°C in all cases and the pouring time is 7-8 seconds. The mould material is green sand and the initial mould temperature is set as 50°C.

3. Calculation of Materials Properties Using JMatPro

JMatPro, an acronym for *J*ava-based *Mat*erials *Pro*perties software, is developed to calculate the materials properties of multicomponent commercial alloys using sound, physically based models [9,10,12,13]. Not only are these properties wide ranging, including density, molar volume, thermal expansion coefficient, thermal conductivity, Young's/shear/bulk modulii, Poisson's ratio, liquid viscosity, specific heat, latent heat and enthalpy, but also they are given from room temperature to the liquid state. Fig. 4 shows examples of the calculated properties of the three materials, including fraction

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Table 1: Compositions of the three candidate alloys used for exhaust manifolds (wt.%).

Alloy name	C	Si	Mn	P	S	Mg	Cu	Mo	Ni	Cr	Fe	Matrix type
M1: FCD500	3.6	2.5	0.3	0.03	0.01	0.01					bal.	Pearlitic
M2: Hi-Si-Mo	3.5	4.2	0.3	0.03	0.01	0.05		0.85			bal.	Ferritic
M3: D5S	2.0	5.0	0.7	0.08	0.02	0.05	0.5		35.0	2.0	bal.	Austenitic

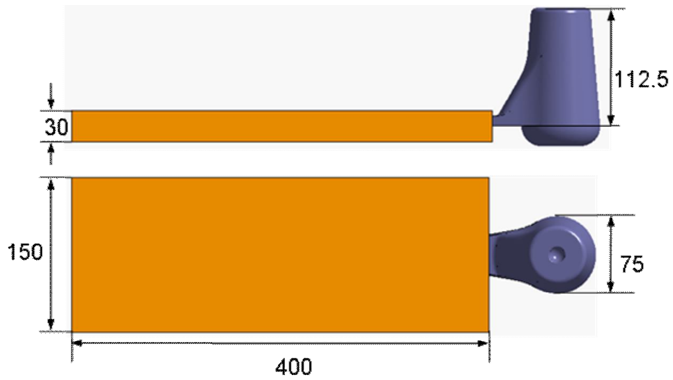

Fig. 1. Simulation setup of feedability test.

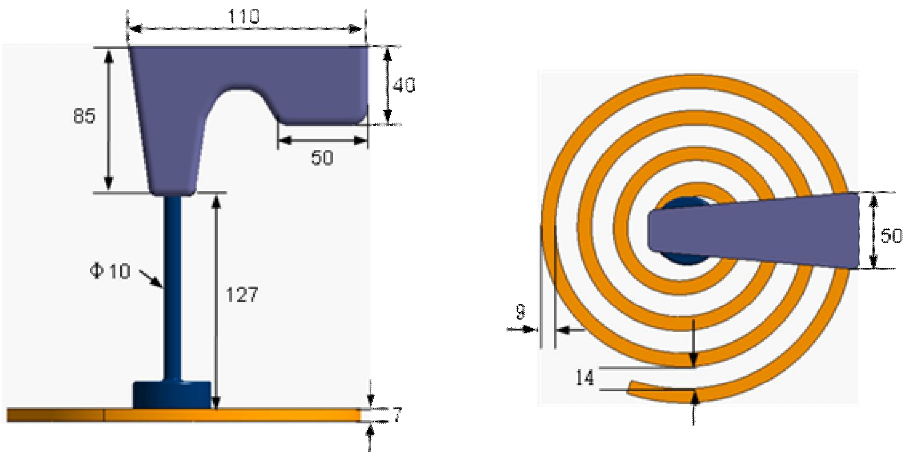

Fig. 2. Simulation setup of spiral type fluidity test.

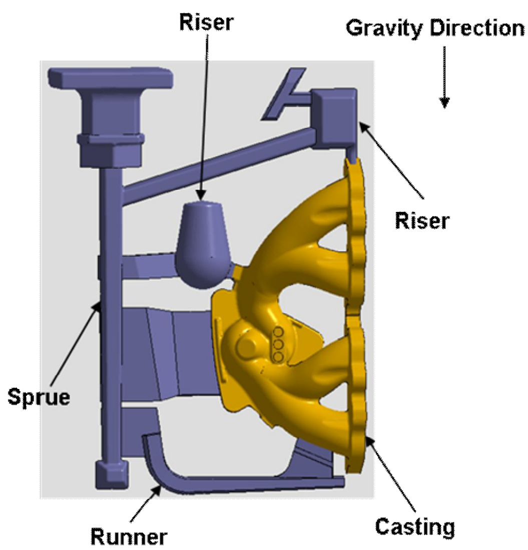

Fig. 3. Setup of sand casting exhaust manifold.

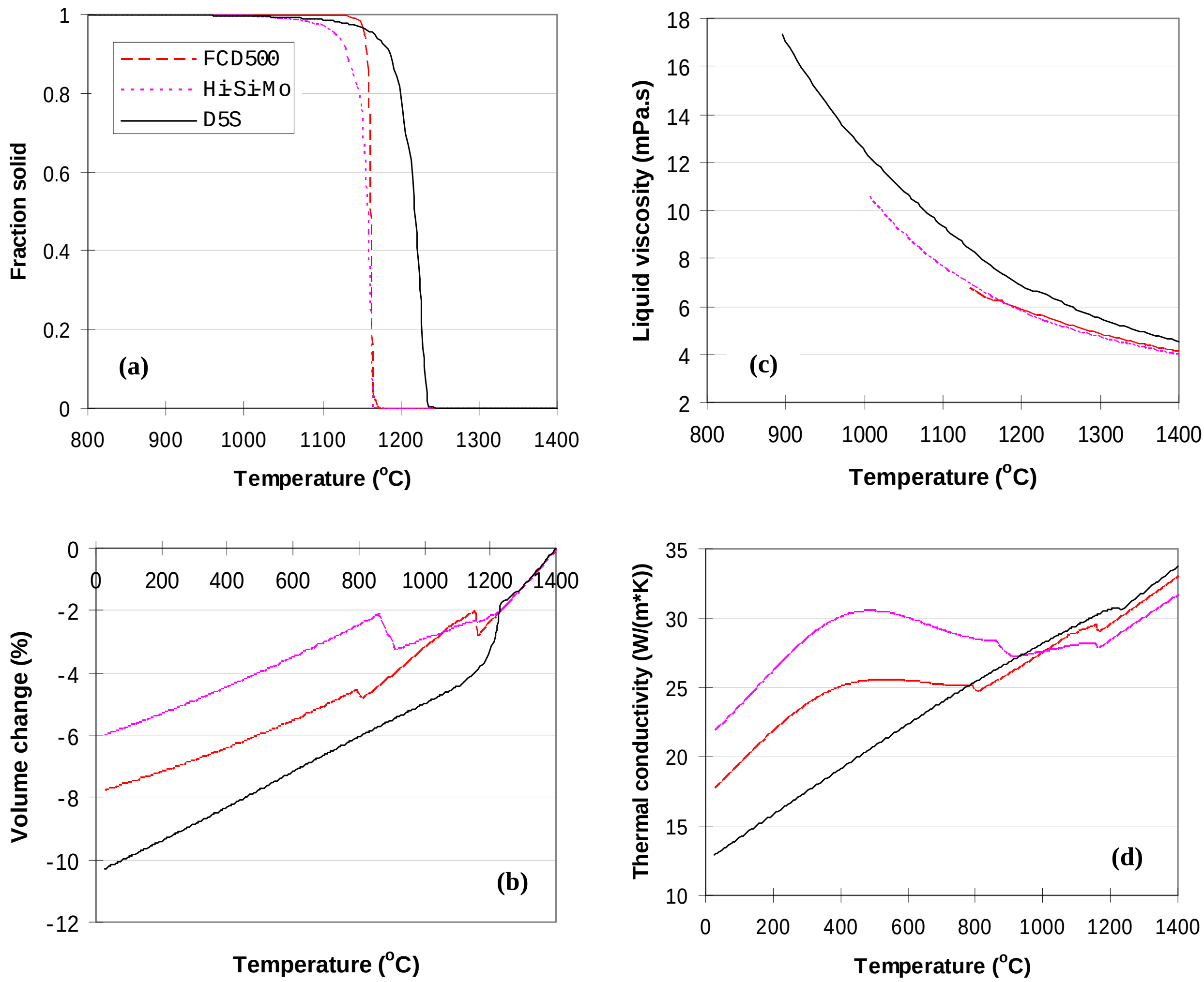

Fig. 4. Calculated material properties of the three candidate materials: (a) fraction solid, (b) volume change, (c) liquid viscosity, and (d) thermal conductivity.

solid, liquid viscosity, volume change, and thermal conductivity, all as a function of temperature. One of the most important factors that affect the structure, particularly the macrostructures, of castings is freezing range. The three alloys have significantly different freezing ranges, Fig. 4(a), whereas FCD500 has the narrowest and D5S, the widest. Cast irons may expand during solidification due to the formation of graphite and this effect has to be reflected in process design. As can been seen from Fig. 4(b), expansion is clearly observed in alloys FCD500 and Hi-Si-Mo, but not D5S. The least carbon content in alloy D5S leads to the least amount of graphite formed during solidification, and no expansion is observed as a result. Viscosity is a measure of a liquid's resistance to flow. A fluid with a low viscosity tends to flow more readily than a high viscosity liquid. One would therefore naturally expect alloy D5S to be more difficult to cast than the other two alloys, based on information in Fig. 4(c).

4. Casting Simulation - AnyCasting

AnyCasting software is an analysis program designed exclusively for casting process. It helps to predict filling and solidification pattern and casting defects. The formation of shrinkage defects is due to a series of complicated factors, which are related to the characteristics of alloy shrinkage, macro- and interdendritic flow of the molten metal and gas release during solidification. There are various models available for shrinkage defect prediction, the Niyama criterion is used in this work.

The Niyama criterion was developed by E. Niyama in 1982 [14], which was used to predict the central-lined shrinkage defects. It can be expressed as $G/L^{0.5}>C$, where G is the temperature gradient and L is the cooling rate. C is the critical constant below which shrinkage defect forms. Since this criterion has no relation with the shape and size of the casting and the parameters used are easily available during the numerical simulation of solidification, it is widely used in shrinkage defect prediction [15,16].

Simulation 1: Feedability Test

Solidification time is one of the important parameters used for assessing the castability of an alloy. Fig. 5 shows the simulated solidification time in the feedability test of the three alloys. It is in the order of D5S < Hi-Si-Mo < FCD500, i.e. alloy FCD500 takes

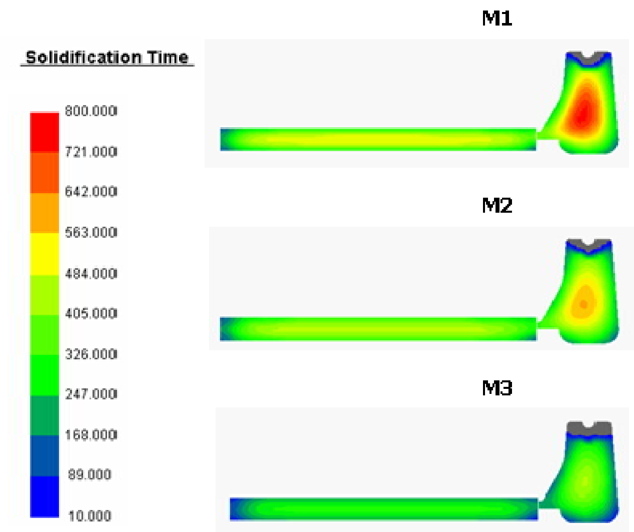

Fig. 5. Simulated solidification time of the three alloys in the feedability test.

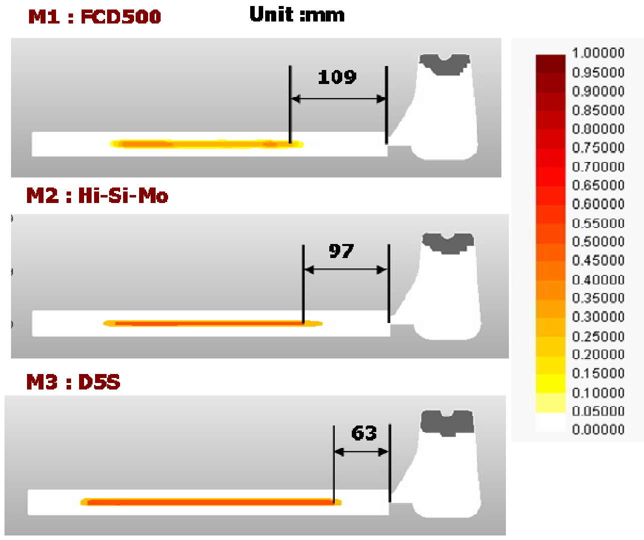

Fig. 6. Feeding distance of the three alloys in the feedability test.

the longest time to complete solidification. Since solidification of molten metals is closely associated with the heat transfer process, a long solidification time is a direct result of low thermal conductivity, the values of which are in the order of D5S > Hi-Si-Mo > FCD500 in the solidification region, Fig. 4(d).

The knowledge of feeding distance is necessary for the proper positioning of casting risers. The simulated feeding distance is 109, 97, and 63mm for alloys FCD500, Hi-Si-Mo, and D5S, respectively, Fig. 6. FCD500 has best feedability, whereas D5S alloy gets the worst.

Simulation 2: Fluidity Test

Fluidity describes the ability of the molten metal to continue to flow while it continues to lose temperature and even while it is starting to solidify. In terms of casting alloys, it is defined as the maximum distance to which the metal will flow in a standard mould. Fig. 7 shows the flow behaviour of the three alloys in the fluidity test. The order is FCD500 (180 mm) > Hi-Si-Mo (125 mm) > D5S (88 mm), i.e. FCD500 has the best fluidity, while D5S alloy has the worst.

Simulation 3: Shrinkage Defect Prediction

Difference in feedability and fluidity results in different defect formation in the simulated casting of the three alloys, Figs. 8 and 9. Alloy D5S, of the worst feedability and fluidity, is unsurprisingly most prone to shrinkage defects. The search for new exhaust materials of better heat resistance results in more and more alloying contents being added. The resulting change in materials properties, such as freezing range and liquid viscosity, usually means these new alloys are more difficult to cast compared with earlier grades. The heat resistance of the alloys studied is in the order of D5S > Hi-Si-Mo > FCD500, whereas the castability is in the reverse order. Better heat resistance usually means compromises in castability, therefore, casting simulation becomes more critical in the design of new exhaust materials. The low castability of alloy D5S means that one cannot apply the same design of runner and risers as that for the other two alloys. More risers have to be added into the current design so as to produce sound and defect-free casting products, which will be the subject of further study.

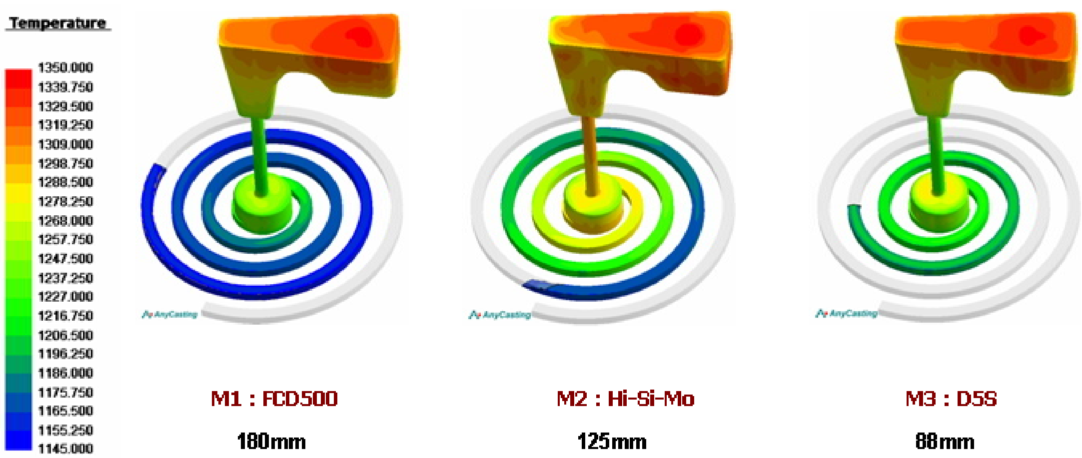

Fig. 7. Simulated flow behaviour of the three alloys in the fluidity test.

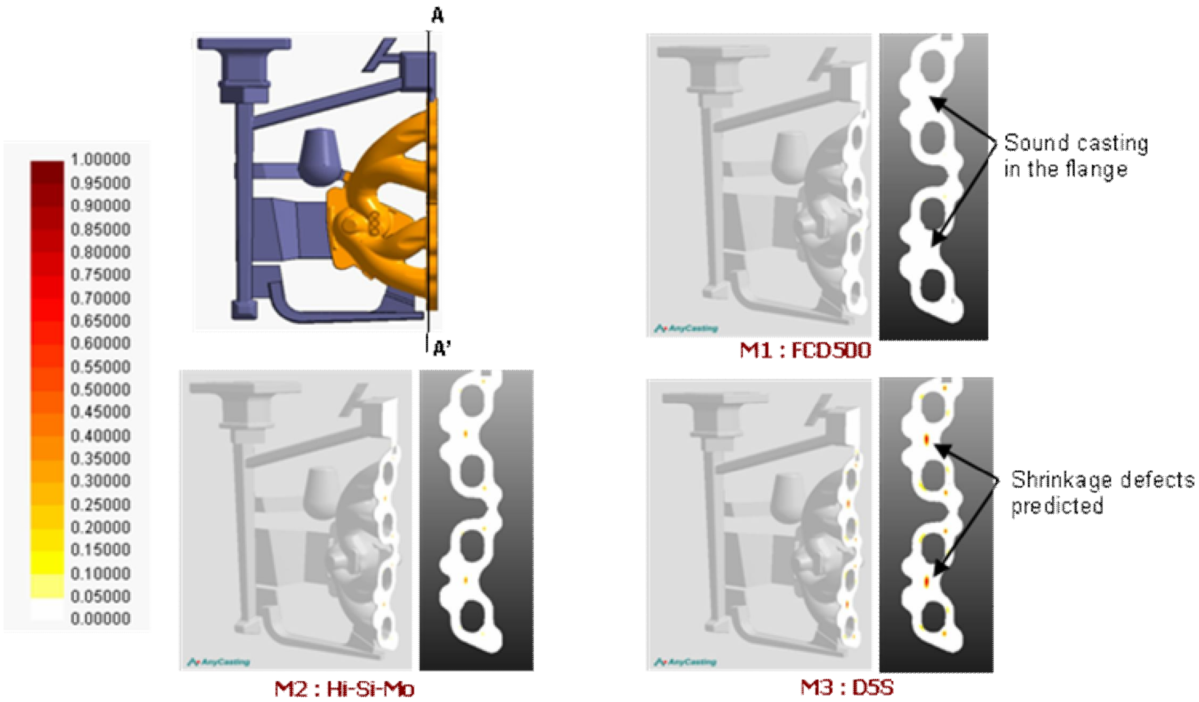

Fig. 8. Shrinkage defect prediction at intersection A-A'.

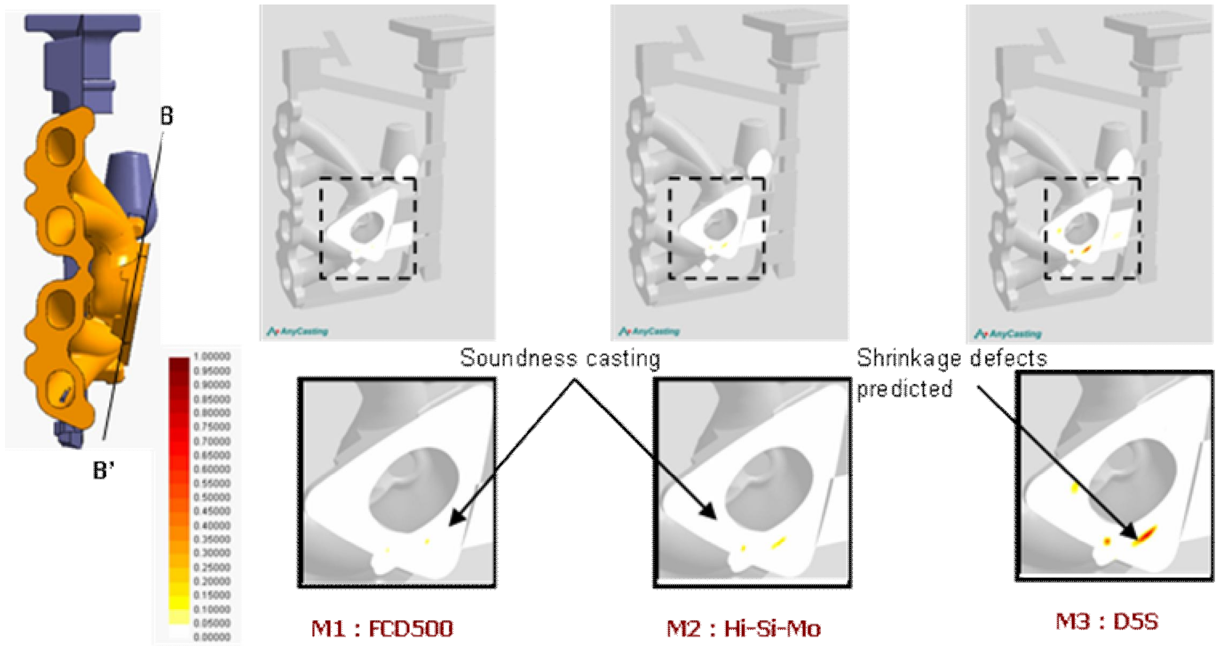

Fig. 9. Shrinkage defect prediction at intersection B-B'.

5. Summary

Increasing addition of alloying contents into materials used for exhaust manifolds to achieve better heat resistance usually means their castability has to be compromised. Therefore, casting simulation becomes very critical in the design of new exhaust materials. This study examines whether sound and defect-free castings can be produced when a new material is considered for exhaust manifolds. The JMatPro software provides a reliable and cost-effective way of generating the material data required by process simulation. Such data has been used as direct input into the simulation package AnyCasting to predict the formation of shrinkage defects in exhaust manifold castings when three alloys are used, namely FCD500, Hi-Si-Mo and D5S. Simulation shows their castability is in the order of FCD500 > Hi-Si-Mo > D5S. As a result, when the same casting design is applied to produce manifold castings, alloy D5S is the material that is most prone to shrinkage defect formation, whereas FCD500 is effectively defect-free. The current design therefore has to be modified for alloy D5S, so as to produce sound and defect-free casting products, e.g., through adding more risers.

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