Materials Science and Engineering A365 (2004) 336–340

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Modelling thermal development of liquid metal flow on rotating disc in centrifugal atomisation

K.H. Ho, Y.Y. Zhao*

Department of Engineering, The University of Liverpool, Brownlow Hill, Liverpool L69 3GH, UK

Abstract

In centrifugal atomisation the formation of a solid skull on the atomising disc is a major problem, which has adverse effects on the quality and quantity of the as-produced powder and also on the balance of the disc during atomisation. It is costly and difficult to study the flow behaviour because of the complex interaction between the liquid metal and the atomising disc. A computational fluid dynamics model has been developed using Flow-3D to simulate the thermal development of the liquid metal on the atomising disc. Under a fixed process condition, the liquid metal has a nearly constant solidification rate before the steady state is achieved and a solid skull is formed gradually. The volume of the skull decreases with increasing liquid metal flow rate, initial disc temperature and initial liquid temperature.

Keywords: Centrifugal atomisation; Atomising disc; Thermal development; Skull formation; Solidification rate

1. Introduction

The centrifugal atomisation process utilises a rapidly-rotating disc to break up a liquid metal stream into a spray of liquid droplets. It is an efficient technology for producing high quality powders and for manufacturing ring shaped components with fine grain structures. In centrifugal atomisation, the interaction between the liquid and the atomising disc is very complex, involving fluid flow, heat transfer and phase transformation [1–5]. It is costly and often difficult to study the flow behaviour on the disc by experiments. Computer modelling is a powerful tool for mechanistic understanding of such a process.

In centrifugal atomisation, the liquid metal flows from a nozzle onto the centre of a rapidly-rotating disc and then spreads towards the disc edge, due to the action of the centrifugal force, followed by the disintegration into a spray of droplets. The atomising disc not only imparts kinetic energy to the liquid but also extracts heat from the liquid. As a consequence, a solid skull is often formed on the disc during centrifugal atomisation due to premature solidification of the liquid metal.

The skull formation is a major problem in centrifugal atomisation. The enlarging skull not only results in undesirable variations in the atomising conditions, reduces the materials yield but can also lead to serious balancing problems. Therefore, the skull build-up needs to be minimised either by selecting appropriate process conditions or by optimising the internal cooling system of the atomising disc. There are a number of parameters which can affect the skull formation in centrifugal atomisation, including the rotating speed, geometry and surface roughness of the atomising disc, the flow rate, melting point, specific heat, solidification latent heat, viscosity and surface tension of the liquid metal, the heat transfer coefficient at the liquid-disc interface and the residence time of the liquid metal on the atomising disc.

This paper develops a computational fluid dynamics model using a commercial software package Flow-3D. The thermal behaviour of the liquid metal on the atomising disc during centrifugal atomisation under different processing conditions, such as different liquid metal flow rates and initial disc temperatures and initial liquid temperatures, is investigated.

2. Model

In practice, centrifugal atomisation is carried out in a circularly symmetrical apparatus. Fig. 1 shows a schematic diagram of the interaction between the liquid metal and the

* Corresponding author. Tel.: +44-151-7944697; fax: +44-151-7944675.

E-mail address: y.y.zhao@liv.ac.uk (Y.Y. Zhao).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2003.09.044

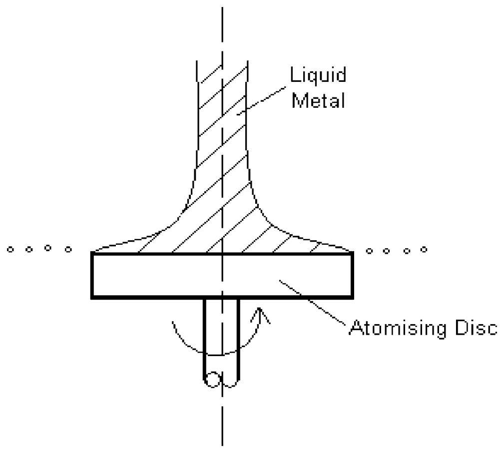

Fig. 1. Schematic of the interaction between the liquid metal and the atomising disc.

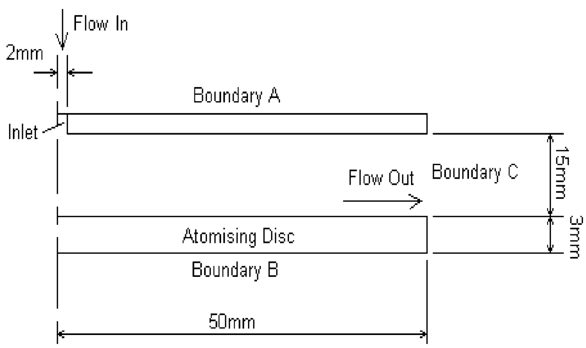

Fig. 2. Dimensions of the computational domain and the setting of the boundaries.

atomising disc. The simulation in this paper is confined to the region where the liquid metal stream impinges and spreads on the atomising disc prior to leaving the disc edge. The computational domain is specified as half of the region in the vertical section through the disc axis taking the symmetry into account. Fig. 2 shows the dimensions of the computational domain and the boundaries at which the fluid and thermal conditions can be specified separately.

The atomising disc is assumed to be made of pure Cu with a surface roughness of 10 μm and to rotate at a constant speed of 5000 rad s^{-1}. The bottom of the atomising disc, Boundary B, is set as a constant-temperature wall because in practice the atomising disc is usually water-cooled. The liquid metal flows in from the inlet into the domain and flows out at Boundary C, which is set as a continuative boundary. The inlet is set as 2 mm in radius and 15 mm from the atomising disc. The top of the domain, Boundary A, is assumed to have the same temperature as the initial liquid temperature. The condition at Boundary A is set to approximate an open air such that it has minimum effect on the flow and thermal behaviour of the liquid metal.

In the simulations, Ti is used as a model metal. The physical properties of solid Cu and those of liquid and solid Ti are assumed to be constant in the temperature ranges under investigation, and are listed in Table 1.

The skull formation under different liquid metal flow rates, initial disc temperatures and initial liquid temperatures is investigated in the simulations by changing only one parameter at a time. The ranges of the liquid metal flow rate, initial disc temperature and initial liquid temperature studied are 0.025–0.25 kg s^{-1}, 300–1000 and 2000–3000 K, respectively.

3. Results and discussion

Fig. 3a–e shows the flow development and the temperature profile of the liquid Ti on the atomising disc from 0.2 to 1.0 s after the liquid metal enters the domain, with a fixed liquid metal flow rate of 0.3 kg s^{-1}, initial disc temperature of 800 K and initial liquid temperature of 2200 K. When the liquid stream impinges and spreads on the disc, solidification of the liquid first takes place at a radius around 0.017 m and a solid skull is rapidly formed. There is a very sharp drop in temperature in the flow around the skull. The weights of the skull corresponding to 0.2, 0.4, 0.6, 0.8 and 1.0 s are 0.35, 0.72, 1.12, 14.3 and 17.6 g, respectively. The volume of the skull stays more or less the same after 1.0 s in most cases and the flow reaches a steady state. The time needed for the liquid metal flow to reach a steady state is dependent upon the process condition.

Fig. 4 shows the development of the skull with time up to 1.0 s, with a fixed liquid flow rate of 0.1 kg s^{-1}, a initial disc temperature of 500 K and an initial liquid temperature of 2800 K. The skull initially forms at a radius of around 0.03 m on the atomising disc and builds up gradually, which is consistent with the experimental observations of the skull formed in the atomisation of a liquid Ti alloy [2,3]. The

Table 1
Physical Properties of Cu and Ti [5–7]

Metal	Cu	Liquid Ti	Solid Ti
Density	8940 kg m^{-3}	4100 kg m^{-3}	4600 kg m^{-3}
Thermal conductivity	400 W m^{-1} K^{-1}	31 W m^{-1} K^{-1}	21.9 W m^{-1} K^{-1}
Specific heat	361 J kg^{-1} K^{-1}	608 J kg^{-1} K^{-1}	522 J kg^{-1} K^{-1}
Melting temperature	1356 K	–	1953 K
Latent heat of melting	–	350 kJ kg^{-1}	–
Viscosity	–	0.0052 N m^{-1} s^{-1}	–
Surface tension	–	1.65 N m^{-2}	–

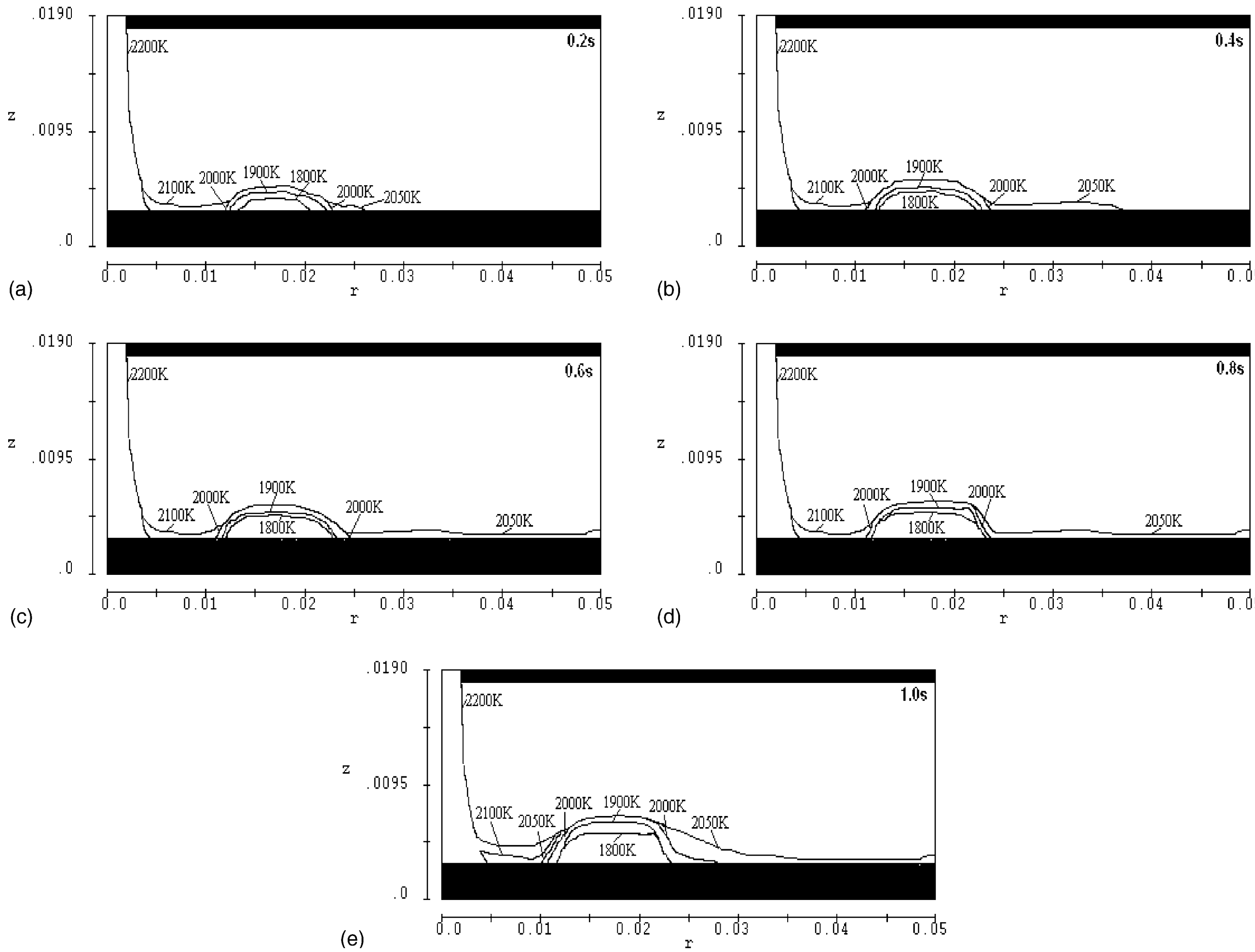

Fig. 3. (a–e) Temperature distributions in the liquid metal flow at different time.

skull develops backwards to the disc centre because the skull serves as an obstacle to the subsequent liquid metal flow and the liquid metal flow becomes slower in front of the skull. The lower the velocity, the more rapid the solidification, because more heat is extracted from the liquid in a unit time.

Fig. 5 shows the variations of the weight of the solid skull with time at different (a) liquid metal flow rates, (b) initial disc temperatures, and (c) initial liquid temperatures. The

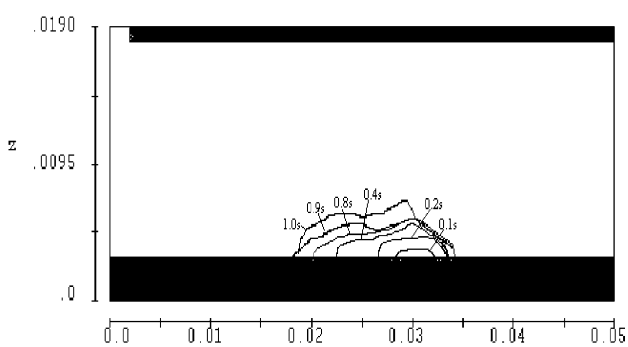

Fig. 4. Development of skull with time.

volume and therefore weight of the skull increases nearly proportionally with time up to 1.0 s, after which it usually ceases to increase and remains constant. In other words, a steady state is established in about 1.0 s. The growth rate of the solid skull decreases with increasing liquid metal flow rate, initial disc temperature and initial liquid temperature.

Fig. 6a–c shows the relationships of solidification rate with liquid metal flow rate, initial disc temperature and initial liquid temperature, respectively. The solidification rate is defined as the weight of the skull increased in unit time. For any of the current simulations, it is nearly constant in the first second. The mean solidification rate within the first second is used in the comparisons.

The solidification rate decreases with increasing liquid flow rate, initially rapidly and then more slowly. At a fixed initial disc temperature and initial liquid temperature, the solidification rate is mainly controlled by the total enthalpy of the liquid on the atomising disc. The higher the liquid metal flow rate, the higher the total enthalpy, and therefore the lower the solidification rate. The residence time of the liquid on the atomising disc also has some effect. At a fixed inlet diameter, the higher the liquid flow rate, the higher the

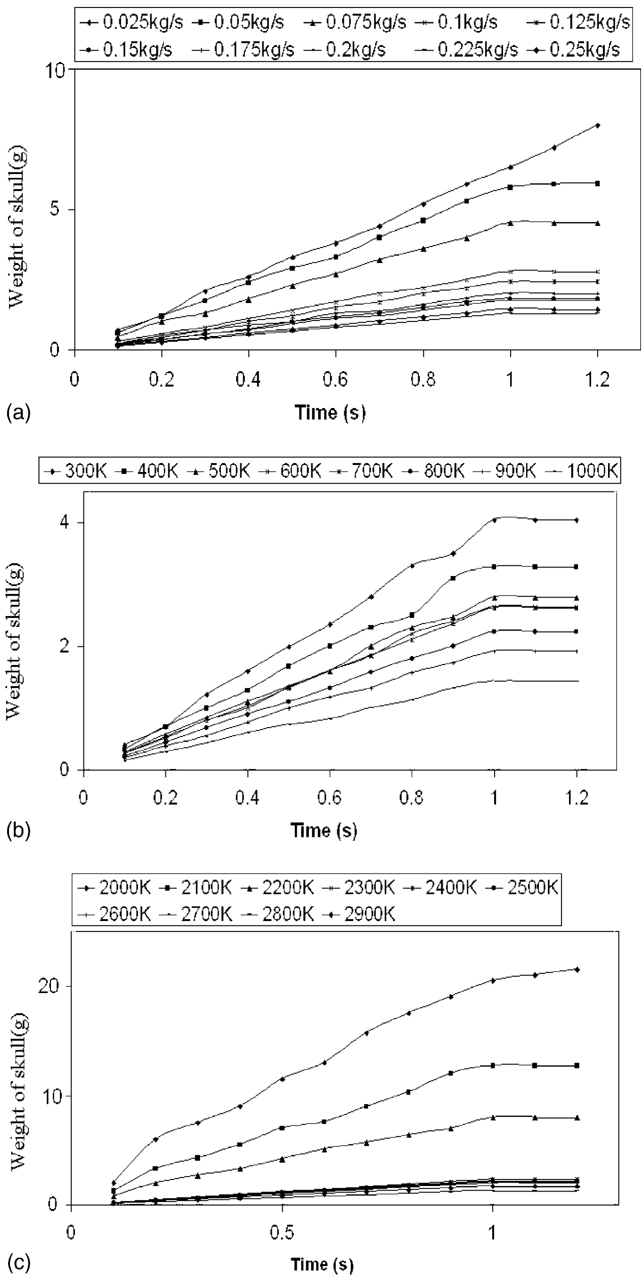

Fig. 5. Growth of skull with time at different (a) liquid metal flow rates, (b) initial disc temperatures and (c) initial liquid temperatures.

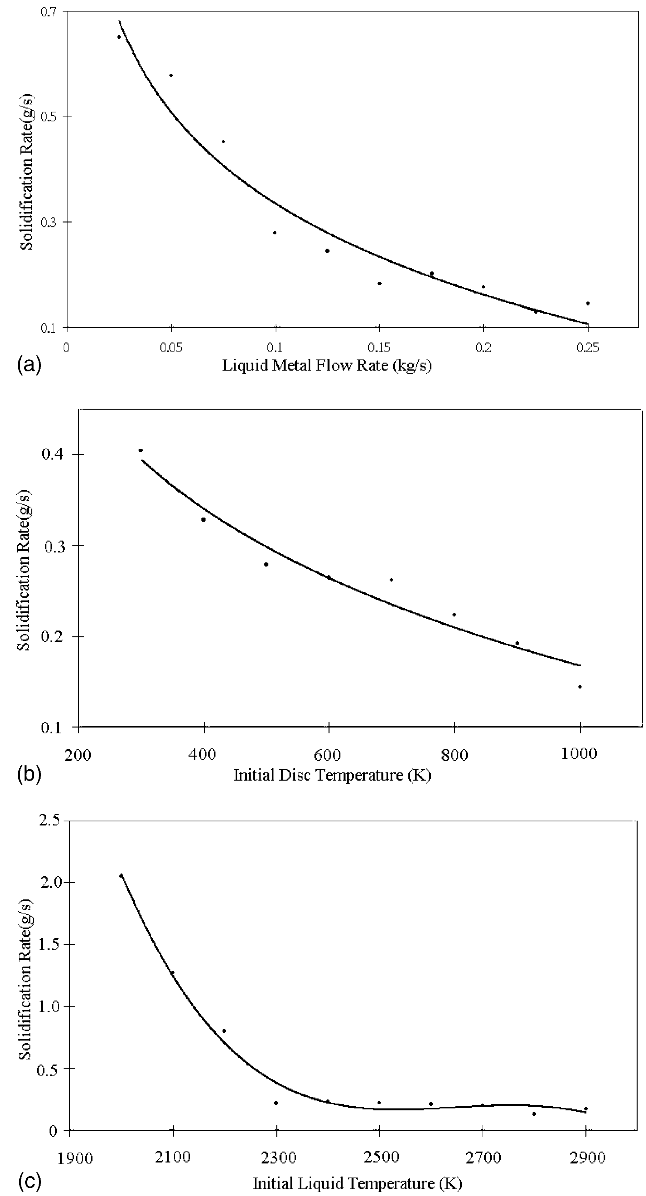

Fig. 6. Relationships of solidification rate with (a) liquid metal flow rate, (b) initial disc temperature and (c) initial liquid temperature.

liquid velocity, and therefore the lower the residence time, leading to lower solidification rate.

The solidification rate decreases steadily with increasing the initial disc temperature. This is because a smaller temperature difference between the liquid metal and the atomising disc leads to a lower heat transfer rate at the interface and therefore a lower solidification rate.

The solidification rate decreases with increasing initial liquid temperature, initially rapidly and then more slowly. On one hand, the higher the initial liquid temperature, the higher the enthalpy of the liquid, tending to result in a lower solidification rate. On the other hand, the higher the initial liquid temperature, the greater the temperature difference between the liquid metal and the disc, and therefore the higher the heat transfer rate, tending to result in a higher solidification rate. It seems that at lower initial liquid temperatures, the former is the dominant factor and at higher temperatures the former and the latter are more or less balanced.

4. Conclusion

A computational fluid dynamics model has been developed to simulate the skull formation on the atomising disc in centrifugal atomisation. Under a fixed process condition, the liquid metal has a nearly constant solidification rate before the steady state is achieved and a solid skull is formed gradually. The volume of the skull decreases with increasing liquid metal flow rate, initial disc temperature and initial liquid temperature.

Acknowledgements

We would like to thank HEFCE and the Wellcome Trust for the provision of computing facilities under a Joint Research Equipment Initiative grant.

References

[1] F. Folio, A. Lacour, Powder Metall. 43 (2000) 245.
[2] Y.Y. Zhao, M.H. Jacobs, A.L. Dowson, Metall. Mater. Trans. 29B (1998) 1357.
[3] Y.Y. Zhao, A.L. Dowson, M.H. Jacobs, Modell. Simul. Mater. Sci. Eng. 8 (2000) 55.
[4] H.P. Li, P. Tsakiropoulos, J. Mater. Synth. Process. 5 (1997) 117.
[5] A.J. Yule, J.J. Dunkley, Atomisation of Melts for Powder Production and Spray Deposition, Clarendon Press, Oxford, 1994, p. 21.
[6] M.J. Donachie, Ti A Technical Guide, ASM International, USA, 1988, p. 11.
[7] J. Szekely, Fluid Flow Phenomena in Metals Processing, Academic Press, USA, 1979, p. 116.