JTTEE 3:216-218
©ASM International

Transport Phenomena in Spray Processing of Structural Materials: An Extended Abstract*

Y. Wu and E.J. Lavernia

The interaction behavior between metallic droplets and ceramic particulates during spray atomization and co-injection is investigated in the present investigation. A model is developed to predict the penetration of ceramic particulates into metallic droplets in the liquid and semi-liquid states. Both surface tension and fluid drag forces are considered in formulating the penetration behavior of ceramic particulates. It is found that the penetration ability of ceramic particulates increases in the sequence: graphite, SiC, Al_2O_3, and TiB_2.

1. Introduction

AN important aspect of discontinuously reinforced metal matrix composite (MMC) fabrication is the incorporation of ceramic reinforcements into metallic matrices. In particular, in the liquid and semisolid processing of particulate-reinforced MMCs, it is often necessary to incorporate ceramic particulates into the matrix materials through stir mixing, centrifugal mixing, or gas injection (Ref 1-5).

Spray atomization and codeposition processes, for example, involve the co-injection of ceramic particulates into a dispersion of matrix droplets under highly nonequilibrium thermal and solidification conditions (Ref 5-7). An example of the interactions that occur between ceramic particulates and alloy droplets during spray atomization and codeposition is shown in Fig. 1. In the processes of spray atomization and co-injection, each particular droplet may be in the liquid, semiliquid, or solid state, depending on factors such as droplet size and solidification kinetics. During the impact with such droplets, ceramic particulates may break through the surface and penetrate the droplets if they possess sufficient kinetic energy.

The complex factors that affect penetration behavior render the prediction of penetration a challenging task. Although experimental evidence has shown that ceramic particulates may penetrate metallic droplets during co-injection, there is still a need for a systematic study of the penetration phenomenon.

2. Interactions between Droplets and Reinforcements

The present investigation examines the penetration behavior of ceramic particulates into metallic droplets during spray atomization and co-deposition. To that effect, Al-4wt%Si-SiC, Al-12wt%Si-SiC, Al-4wt%Si-TiB_2, and aluminum-graphite composite powders were synthesized using a spray atomization and co-injection approach. The penetration of ceramic particu-

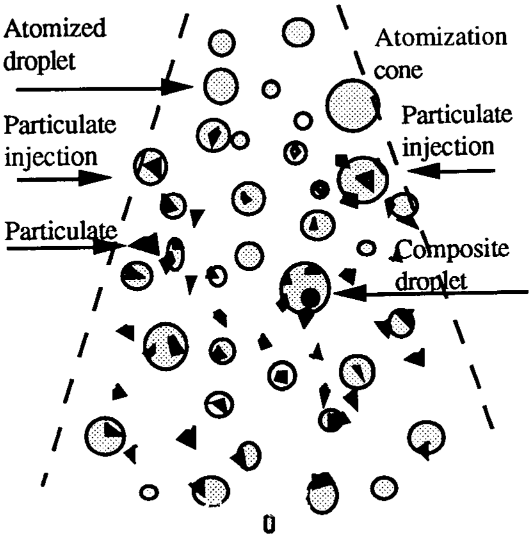
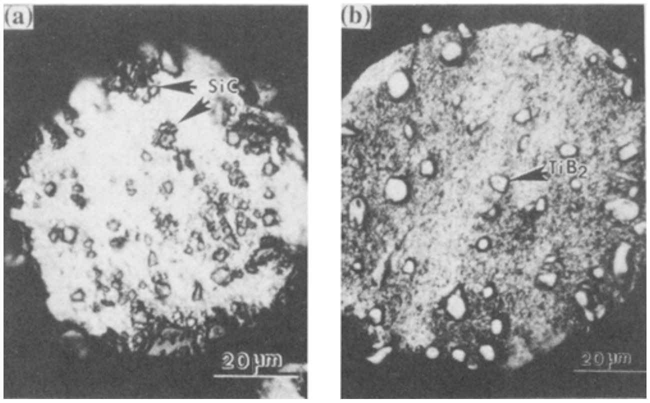


Fig. 1 Schematic diagram showing the interactions between ceramic particulates and metallic droplets during spray atomization and co-injection



(a) (b)

Fig. 2 The presence of ceramic particulates in aluminum-silicon powders prepared by spray atomization and co-injection. (a) SiC. (b) TiB_2

Key Words: interactions, metal-matrix composites, penetrating spray deposition, SiC particulates

Y. Wu and **E.J. Lavernia,** Materials Science and Engineering, Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA 92717

*Extracted from the *Symposium on Spray Forming*, paper 1 of 12 contributions, National Thermal Spray Conference, Anaheim, June 1993. This abstract has been edited by C.C. Berndt (SUNY at Stony Brook).

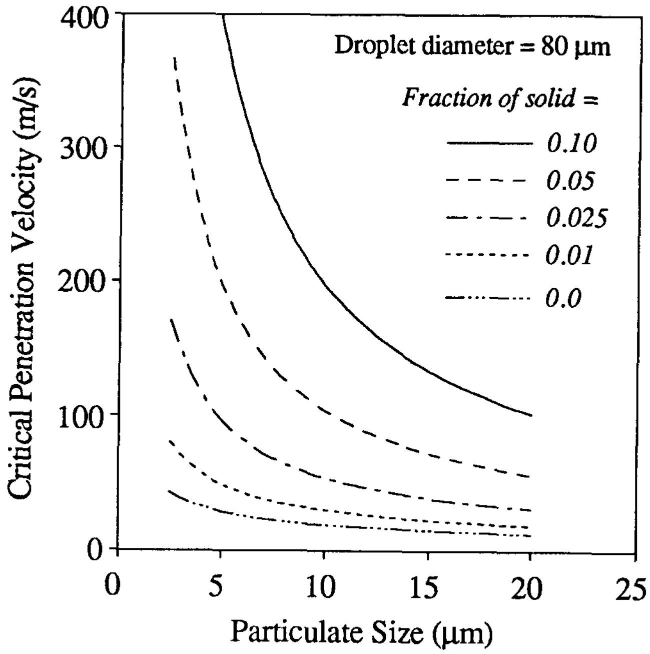


Fig. 3 The critical penetration velocity of SiC plotted as a function of particulate size for various fractions of solid

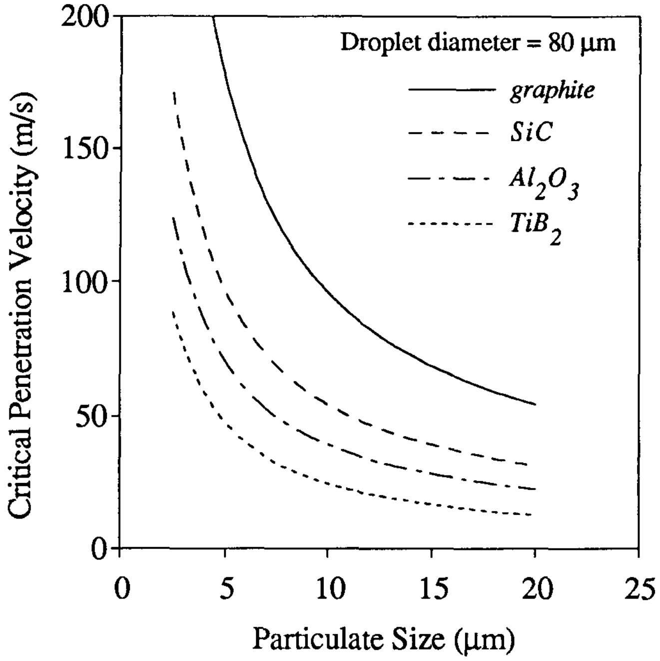


Fig. 4 The critical penetration velocity plotted as a function of particulate size for various ceramic particulates (droplets contain 2.5% solid phase)

lates into atomized droplets was characterized by quantitative metallography. The results show that ceramic particulates were incorporated into the droplets. The example in Fig. 2 shows the presence of TiB_2 particulates in aluminum-silicon droplets. The extent of penetration, however, was found to depend critically on the solidification condition of the droplets and the physical properties of the ceramic particulates. Accordingly, extensive incorporation was found in the Al-SiC and Al-TiB_2 systems; however, incorporation of graphite particulates in the aluminum-graphite system was not commonly observed.

3. Modeling of Interactions

To provide insight into the penetration behavior of ceramic particulates into metallic droplets, a theoretical model was developed that incorporated the effects of wetting characteristics and the physical properties of the ceramic particulates. The model considered both the surface tension of the liquid alloy and fluid drag effects. The penetration depth of ceramic particulates was calculated by considering the force balance during penetration. The force acting on a particulate, F_r, was calculated from:

$$F_r = F_s + F_d \tag{Eq 1}$$

where F_s is the force due to surface energy change induced by penetration and F_d is the fluid drag force due to the motion of the particulate in the droplet. Furthermore, F_s and F_d may be calculated from:

$$F_s = \frac{dS_{pl}}{dx}\gamma_{lg}\cos\theta - \frac{dS_d}{dx}\gamma_{lg} \tag{Eq 2}$$

and

$$F_d = -\frac{1}{2}S\rho V^2 f \tag{Eq 3}$$

where S_{pl} is the contact area between the particulate and the droplet, S_d is the area of the droplet, S is the projected area of the particulate in its moving direction, γ_{lg} is the interfacial energy, θ is the wetting angle between the particulate and the liquid alloy, x is the coordinate in the particulate moving direction, V is the particulate velocity, ρ is the density of the alloy that forms the droplets, and f is a frictional factor (Ref 8).

4. Results and Discussion

In the present investigation, the critical penetration velocity (i.e., the initial velocity of particulates at which the penetration depth of the particulate equals particulate size) was defined as the criterion of penetration. By using this model, the factors that affect the penetration include the density of the ceramic particulate, the wetting angle between the particulate and the liquid alloy, the fraction of solid contained in the semiliquid alloy, and the surface tension of the liquid alloy (Fig. 3). Accordingly, it was found that the critical velocity required for penetration increased with increasing wetting angle and fraction of solid, but decreased with increasing particulate density. Alternatively, for each given velocity, a minimum size of particulates was found that can penetrate the droplets. Finally, the penetration ability of ceramic particulates was defined by the area underneath the critical penetration velocity versus the minimum particulate size curve. When the various ceramic particulates that are normally encountered in MMCs were compared, penetration ability was found to decrease in the following sequence: TiB_2, Al_2O_3, SiC, and graphite (Fig. 4).

Acknowledgments

The authors wish to acknowledge the National Science Foundation (Grant DDM 8957449) and the Army Research Office (Grant DAALO3-92-G-0181) for financial support.

References

1. A. Mortensen, J.A. Cornie, and M.C. Flemings, Solidification Processing of Metal-Matrix Composites, *J. Met.*, Vol 40 (No. 2), 1988, p 12-19
2. P.K. Rohatgi, R. Asthana, R.N. Yadav, and S. Ray, Energetics of Particle Transfer from Gas to Liquid during Solidification Processing of Composites, *Metall. Trans. A*, Vol 21, 1990, p 2073-2082
3. P.K. Rohatgi, The Solidification of Metal-Matrix Particulate Composites, *J. Met.*, Vol 43 (No. 5), 1991, p 35-41
4. A.S. Kacar, F. Rana, and D.M. Stefanescu, Kinetics of Gas-to-Liquid Transfer of Particles in Metal Matrix Composites, *Mater. Sci. Eng. A*, Vol 135, 1991, p 95-100
5. Y. Wu and E.J. Lavernia, Interaction Mechanisms between Ceramic Particles and Atomized Metallic Droplets, *Metall. Trans. A*, Vol 23, 1992, p 2923-2937
6. M. Gupta, F.A. Mohamed, and E.J. Lavernia, The Effect of Ceramic Reinforcements during Spray Atomization and Codeposition of Metal Matrix Composites: Part I Heat Transfer, *Metall. Trans. A*, Vol 23, 1992, p 831-844
7. I.A. Ibrahim, F.A. Mohamed, and E.J. Lavernia, Particulate Reinforced Metal Matrix Composites—A Review, *J. Mater. Sci.*, Vol 26, 1991, p 1137-1156
8. G.H. Geiger and D.R. Poirier, *Transport Phenomena in Metallurgy*, Addison-Wesley, 1973, p 36-110