1 Introduction to Transport Phenomena in Materials Processing

1.1 TRANSPORT PHENOMENA

In any effort, it is wise to start by clearly stating the purpose of the endeavor. Our goal in writing this textbook is to help future and practicing engineers better understand and predict the behavior of mass, momentum, heat, and species movement, especially during materials processing. The study of the movement of these quantities is the field of *transport phenomena*.

Before progressing with this topic, we should address an important question regarding transport phenomena: why should materials engineers find time to study this topic, either during a university degree program or on their own? There are many interesting and useful subjects to learn and a very finite amount of time available, so a case must be made, in a cramped curriculum or in a busy professional life, for the allocation of scarce time to this subject instead of many other interesting alternatives.

While many engineers are concerned with transport phenomena for their own sake, the materials engineer heats, cools, pours, pumps, and diffuses materials in the pursuit of *beneficial materials properties*, to make the material economical to produce in the first place. (An example is age-hardened aluminum alloys, which make the aerospace industry possible and would not have the required mechanical properties without heating- and cooling-induced and mass diffusion–controlled solid-solid phase transformations [1]. Other examples are described in the next section.) The transport phenomena (along with the phase equilibria in the material) are the mechanisms that produce many material properties throughout processing by the control of microstructure development. This interrelationship is illustrated by the oft-cited "MSE triangle" shown in Figure 1.1. The three vertices of this triangle are interdependent, and understanding the physical mechanisms of transport phenomena is necessary to understanding many of these relationships.

The primary approach we will use here to improve our understanding and our predictions is the making of models of the transport phenomena. These models are *mathematical representations of reality*, not reality itself. In an excellent description of model-making methodology in materials science and engineering, Ashby [2] wrote:

> A model is an idealization . . . (it) unashamedly distort(s) the inessentials in order to capture the features that really matter. . . . At best, it captures the essential physics of the problem, it illuminates the principles that underline the key observations, and it predicts behavior under conditions which have not yet been studied.

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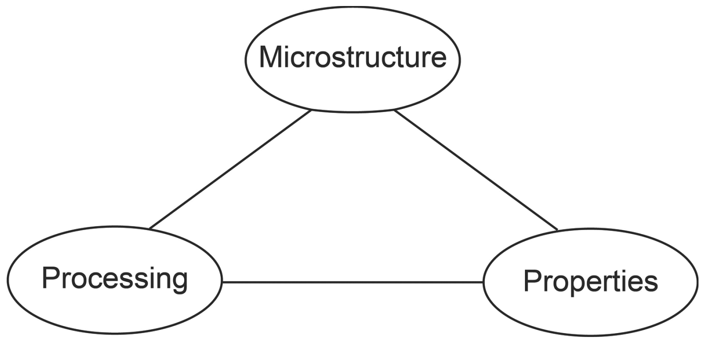

FIGURE 1.1 The “MSE triangle,” a representation of the primary, interconnected aspects of materials science and engineering.

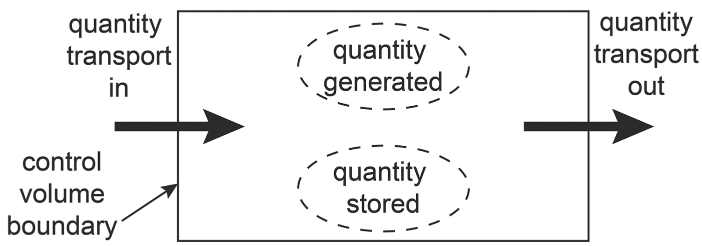

FIGURE 1.2 Balance of generic quantity transport in control volume.

In this text, we will follow Ashby’s lead with the goal of understanding and estimating the behavior of transport phenomena in materials processing.

The simplest way to arrange our thinking about many models of transport phenomena is in terms of a *control volume*, a fixed portion of space through and in which we observe the motion of some quantity. Figure 1.2 shows a schematic of transport in a control volume, which leads to a very general balance:

$$\text{quantity in} - \text{quantity out} + \text{quantity generated} = \text{quantity stored} \tag{1.1}$$

Mass, momentum, heat, and species each have their own possible mechanisms of transport across a control volume boundary and generation (or destruction) in the volume, and these mechanisms and how to model them are the subject of much of this text. The sum of these three phenomena is not necessarily zero, but is the amount accumulated in (or depleted from) the control volume. For example, momentum can be added to a control volume through pressure gradients, buoyancy, or friction, all of which can drive a fluid’s acceleration (storing momentum) or transport through the volume. Heat might be generated by a chemical reaction and transported across the boundary by thermal radiation. Most of the models of transport here will be derived starting from the simple balance in Eq. (1.1).

1.2 EXAMPLES OF TRANSPORT PHENOMENA IN MATERIALS PROCESSING

The study of transport phenomena is sometimes divided into three areas: fluid flow, heat transfer, and mass transfer. To drive home the importance of transport phenomena in materials processing, we show in this section some examples of industrial processes in which these phenomena have a significant effect on their behavior.

1.2.1 Fluid Flow

The shot peening process work hardens a metal surface by high-speed bombardment of that surface by small steel shot. One method of the production of that shot is sketched in Figure 1.3. Steel is melted in one furnace and then poured into the holding furnace in the figure, which in turn is drained in a controlled manner. The jet of liquid steel pouring from the holding furnace is intercepted by a high-speed water spray. The interaction of these two jets fractures the steel stream, atomizing it into a cloud of quickly frozen metal droplets. The size distribution of steel shot is a strong function of the water and steel stream velocities and the angle at which they interact [3]. Controlling the water spray velocity is done through the design of a piping system, taking into account frictional losses in the circuit and the spray nozzle and the behavior of the pump. That flow is typically steady, but the exit jet velocity of the steel and the angle at which it enters the water spray change substantially during the draining, as they are strong functions of the height of the fluid above the nozzle. In Chapter 6, methods for characterizing the steel jet behavior are explored. The physics of the liquid metal's atomization are beyond the scope of this text; interested readers are referred to monographs on that topic [3, 4].

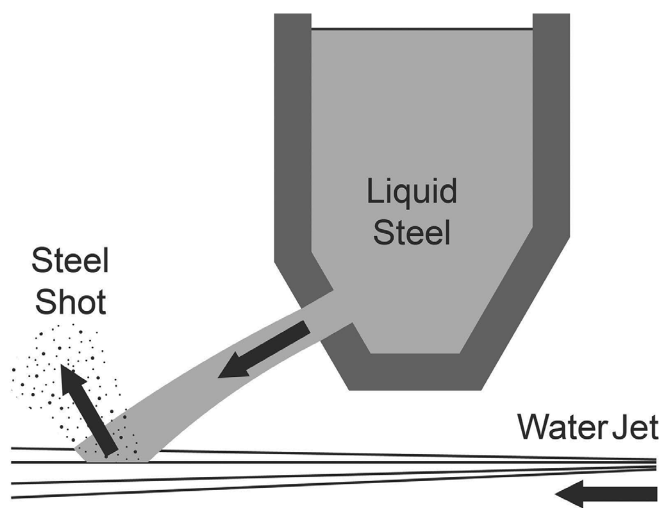

FIGURE 1.3 Atomizing a steel stream draining from a holding furnace. The water jet fractures the steel into a range of small droplet sizes.