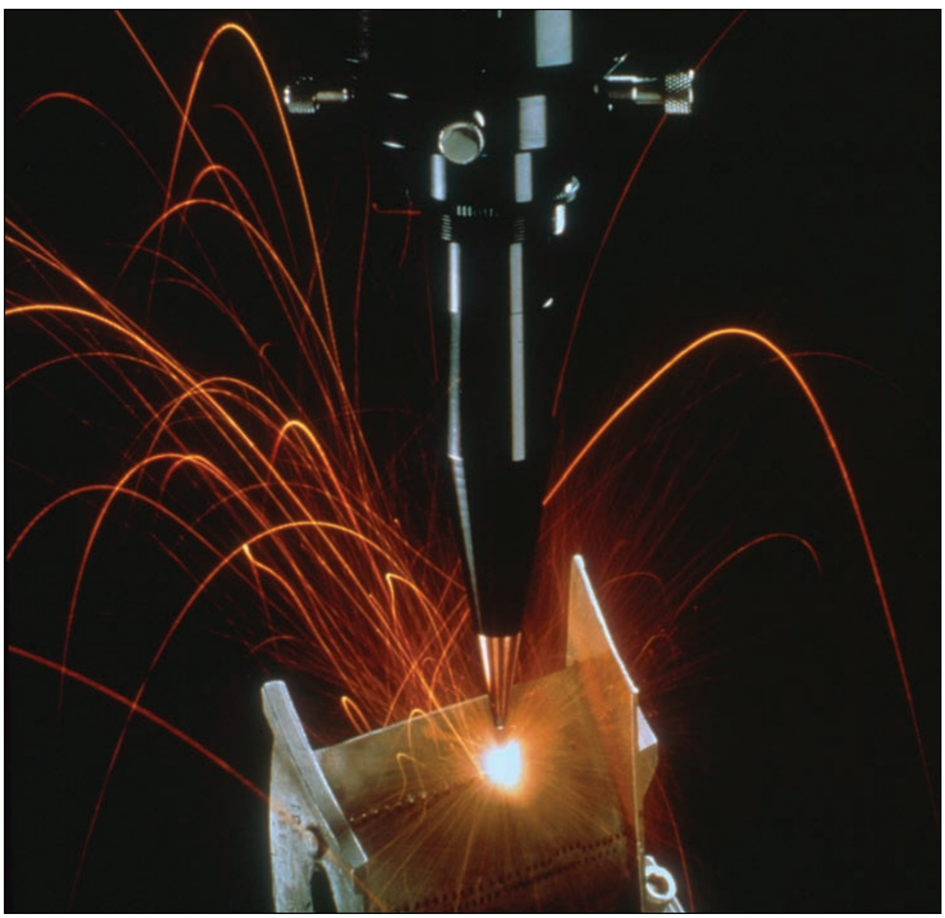
CHAPTER 3

HEAT FLOW IN WELDING



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INTRODUCTION

During fusion welding, the interaction between the base metal and the heat source leads to the rapid heating and melting and the vigorous circulation of molten metal. In the weld pool, the circulation of this molten metal is driven by buoyancy; the surface tension gradient, jet impingement, or friction; and, when electric current is used, electromagnetic forces. The resulting heat transfer and fluid flow affect the transient temperature distribution in the base material, the shape and size of the weld pool, and solidification behavior.

The variation of temperature with time, often referred to as the *thermal cycle*, affects microstructures, residual stresses, and the extent of the distortions in the weldment. On the surface of the weld pool, the temperature distribution affects the loss of alloying elements by evaporation as well as the absorption and desorption of hydrogen and other gases. Thus, the composition of the weldment is affected. In the interior of the weld pool, inclusions grow or dissolve, depending on the local temperature. The control of these temperature fields and cooling rates is essential to ensure sound welds with the desired fusion-zone geometry, chemical composition, and microstructure, as well as with low residual stress and distortion.

An understanding of heat transfer is important in the production of welds inasmuch as the properties of a weldment are controlled by its geometry and by the composition and structure of the materials being welded. The measurement of the temperature fields that form on the surface of the weld pool and in the weldment provides important information about heat transfer characteristics.

However, the measurement of surface temperatures during fusion welding is difficult. Although reliable techniques are being developed, such measurements are fairly complex and require specialized equipment. With respect to the measurement of temperature within the molten weld pool, no reliable technique currently exists. Temperature measurements in the solid regions commonly involve the placement of thermocouples, which are cumbersome and expensive, in holes drilled in the plates. Therefore, a recourse is to use quantitative calculations to gain insight into the phenomenon of heat transfer during fusion welding.

The fundamentals of heat transfer in fusion welding are examined in this chapter. The discussion focuses on arc, laser, and electron beam welding. In all welding, only a fraction of the energy dissipated by the heat source is actually absorbed by the base metal. Arc efficiency is an important parameter for the measurement of absorption efficiency in heat transfer during arc welding processes. In laser and electron beam welding, the proportion of energy absorbed by the metal is important. Thus, the factors responsible for the efficiency of energy absorption by the base metal are also discussed here.

In the weld pool, heat is transported by means of convection and conduction. Therefore, this chapter presents heat conduction calculations and several more advanced calculations that consider heat transfer by both conduction and convection in fusion welding. Because of its complexity, convective heat flow during welding cannot be solved analytically. As a result, the heat flow calculations made in the past were often limited to a simplified heat conduction calculation. Nonetheless, these heat conduction calculations provide a fairly simple and useful insight into fusion welding.

With the advent of high-speed computers, more realistic and accurate heat transfer calculations that take into consideration both conduction and convection can now be performed numerically. These complex calculations can accurately predict weld pool geometry, weld metal composition, and, in simple systems, weldment structure.

HEAT FLOW FUNDAMENTALS

The principal characteristics of the transfer of thermal energy from the welding arc to the workpiece and within the workpiece itself are reviewed in this section. These characteristics determine the maximum or peak