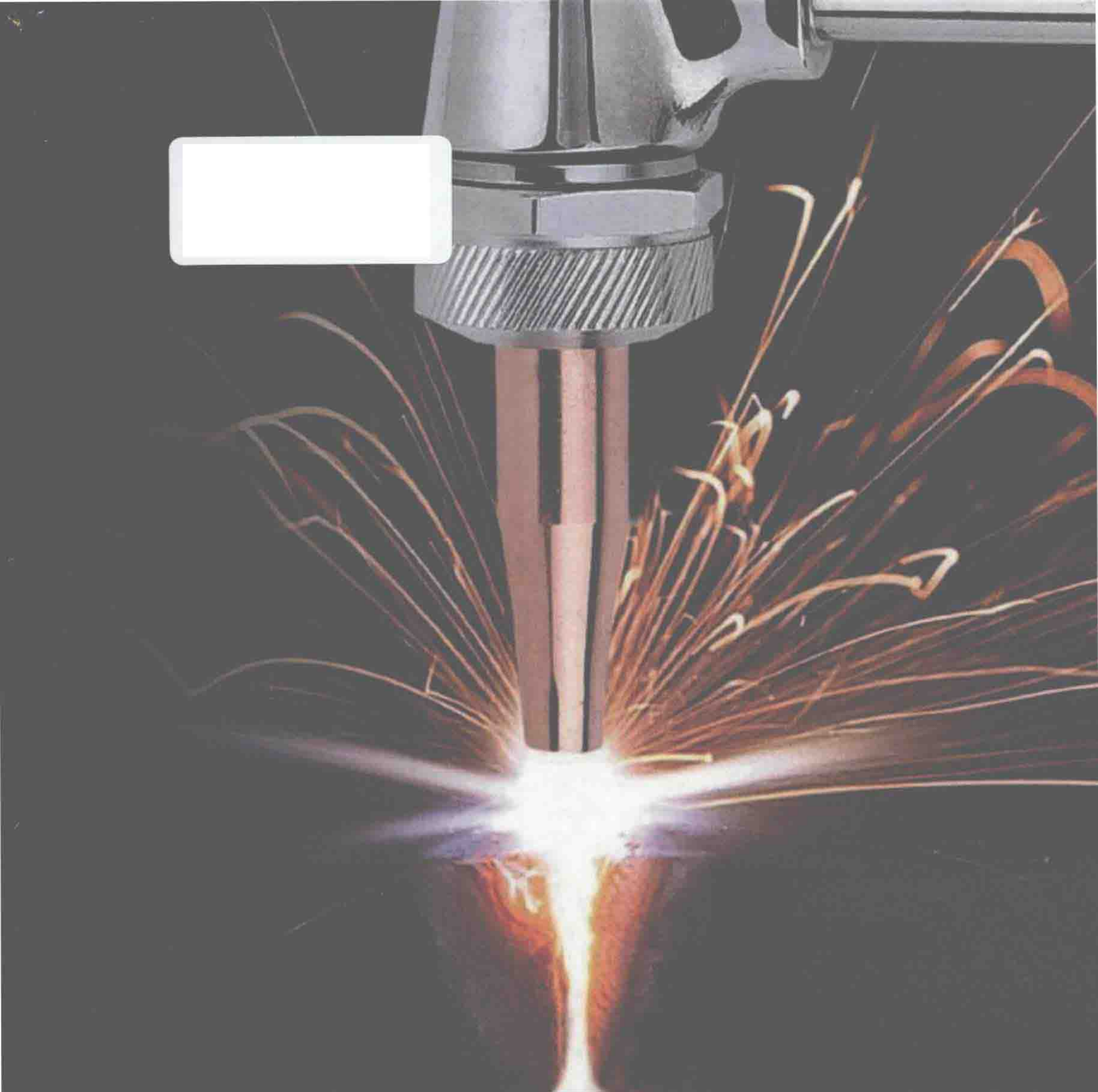

Welding Databook

Howard Currant

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Edited by **Howard Currant**

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Preface

The processes of welding are explained thoroughly in this elaborative book. Although there is a broad range of available literature on welding processes, a demand still exists to regularly update the engineering community on advancements in joining techniques of similar and dissimilar materials, in their numerical modelling, as well as in their sensing and control. This book has been compiled by a group of authors from different countries across five continents who joined hands to co-author this book on welding processes, giving detailed insight to the reader. Some of the main topics discussed here are sensing of welding procedures, welding of laser and numerical modelling.

Various studies have approached the subject by analyzing it with a single perspective, but the present book provides diverse methodologies and techniques to address this field. This book contains theories and applications needed for understanding the subject from different perspectives. The aim is to keep the readers informed about the progress in the field; therefore, the contributions were carefully examined to compile novel researches by specialists from across the globe.

Indeed, the job of the editor is the most crucial and challenging in compiling all chapters into a single book. In the end, I would extend my sincere thanks to the chapter authors for their profound work. I am also thankful for the support provided by my family and colleagues during the compilation of this book.

Editor

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Section 1

Laser Welding

Hybrid Laser-Arc Welding

J. Zhou and H.L. Tsai

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1. Introduction

Hybrid laser-arc welding has received increasing interest in both academia and industry in last decade[1,2]. As shown in Fig. 1, hybrid laser-arc welding is formed by combining laser beam welding and arc welding. Due to the synergic action of laser beam and welding arc, hybrid welding offers many advantages over laser welding and arc welding alone[3-6], such as high welding speed, deep penetration[7], improved weld quality with reduced susceptibility to pores and cracks[8-16], excellent gap bridging ability[17-22], as well as good process stability and efficiency, as shown in Fig. 2.

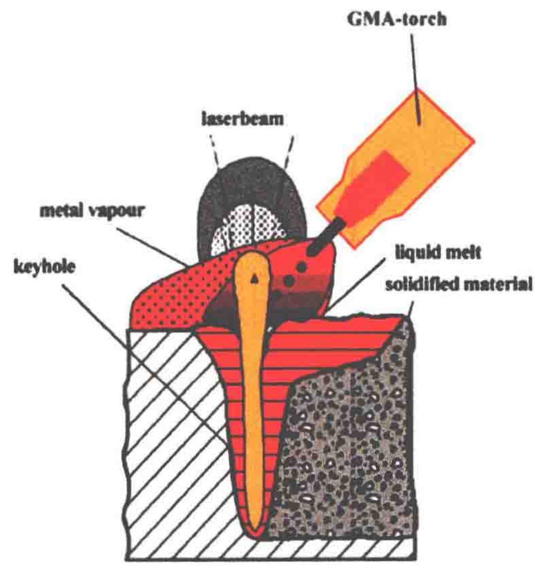

Figure 1. Schematic sketch of a hybrid laser-arc welding process.

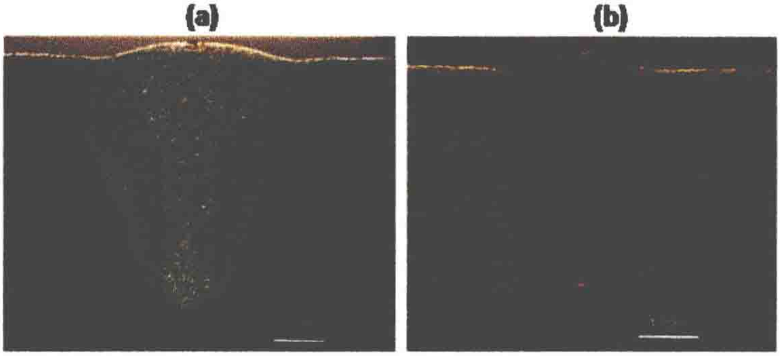

Figure 2. Comparison between (a) a laser weld and (b) a hybrid laser-arc weld in 250 grade mild steel.

Development of the hybrid laser-arc welding technique can be divided into three stages[1]. The concept of hybrid laser welding was first proposed by Steen *et al.*[3, 23, 24] in the late seventies. In their studies, a CO_2 laser was combined with a tungsten inert gas (TIG) arc for welding and cutting applications. Their tests showed clear benefits of combining an arc and a laser beam in the welding process, such as a stabilized arc behavior under the influence of laser radiation; a dramatic increase in the speed of welding of thin metal sheets; and an increase in penetration depth compared with laser welding. Japanese researchers continued Steen's effort and developed various methods and corresponding devices for laser-arc welding, cutting, and surface treatment. However, these efforts did not advance this joining technique into engineering applications particularly because laser welding itself was not yet an economic and viable joining technique at that time[25]. In the second stage of the development of the hybrid laser-arc welding technique, the observed influence of the arc column behavior by laser radiation was used to improve the efficiency of arc welding processes, which leads to the laser-enhanced arc welding technology[1]. A characteristic feature of this technology was that only a low-intensity laser beam was needed, i.e., the required laser power was small compared to the arc power. For TIG welding, Cui and Decker[26-28] demonstrated that a low-energy CO_2 laser beam with a power of merely 100 W could facilitate arc ignition; enhance arc stability; improve weld quality; and increase welding speed due to a reduced arc size and higher arc amperages. However, despite such reported improvements of the arc welding process through laser support, there were neither subsequent extensive investigations of this subject nor known industrial applications of the laser-enhanced arc welding technology. The third stage of hybrid welding technology started in the early 1990s with the development of combined welding processes using a high-power laser beam as the primary and an additional electric arc as the secondary heating source[29-37]. At that time, although the continuous wave CO_2 laser welding process was already well established in industry, it had some known disadvantages, e.g., high requirements of edge preparation and clamping; fast solidification leading to material-dependent pores and cracks; as well as the high investment and operating costs for the laser equipment. Additionally, some welding applications of highly practical interest could not be solved satisfactorily by the laser welding process alone, e.g., joining of tailored blanks in the automotive engineering; welding of heavy plates in shipbuilding industry; as well as high speed welding of crack-susceptible materials. In searching for suitable solutions, the hybrid laser welding was developed into a viable joining technique with significant industrial acceptance during the last decade.

According to the combination of various heating sources used, hybrid welding can be generally categorized as: (1) laser-gas tungsten arc (GTA) welding; (2) laser-gas metal arc (GMA) welding; and (3) laser-plasma welding[25]. Since laser welding offers deep penetration, primary heating sources commonly used in hybrid welding are CO_2, Nd:YAG, and fiber lasers. The first two types of lasers are well established in practice and used for various hybrid welding process developments. While the fiber laser is still in development for industrial applications, it seems to be a future primary heating source for hybrid welding due to its high beam quality. The secondary heating sources used in hybrid welding are mainly electric arcs. Dedicated processes can be divided into GMA welding with consumable electrodes and GTA welding with non-consumable tungsten electrodes. In GMA welding, the arc is burning between a mechanically supplied wire electrode and the workpiece. The shielding gas used in GMA welding was found to have significant effects on arc shape and metal transfer[38,39]. Hence, GMA welding can be subdivided into metal inert-gas (MIG) and metal active-gas (MAG) welding according to the type of shielding gas used. In GTA welding, a chemically inert gas, such as argon or helium, is often used. A special form of this is the plasma arc welding (PAW), which produces a squeezed arc due to a special torch design and results in a more concentrated arc spot.

In hybrid welding, laser and arc are arranged preferably in a way that they can compensate and benefit from each other during the welding process, which implies the creation of a common interaction zone with changed characteristics in comparison to the laser welding and the arc welding alone. In contrast to this is the arrangement in which laser and arc are serving as two separate heating sources during the welding process. Several configurations have been proposed. In a parallel arrangement, there is a distance in either the vertical or horizontal direction along the path between both heating sources. In a serial arrangement, the primary and secondary heating sources are moved along the same welding path with a certain working distance, and the secondary heating source can either lead or follow the primary heating source[1]. The first one enables a preheating of the region to be welded. It can increase the efficiency of the laser welding process because materials to be welded are locally preheated and energy losses through heat conduction are reduced. In comparison, the second one often acts like a short-time post-heat treatment of the weld that can change the weld microstructure favorably. There exists a key difference between parallel and serial process arrangement. In a serial arrangement, additional energy is dissipated within the weld seam region, whereas in the parallel arrangement, the heat flow is reduced only across the weld seam. The option to move the working area temporally enables flexibility in influencing the cooling rates in order to avoid defects.

In the hybrid laser-arc welding process, the workpiece is first heated up and melted due to the laser irradiation. The plasma arc between the consumable electrode and the workpiece continues to heat up and melt the base metal and the droplets generated at the electrode tip periodically detach and impinge onto the workpiece. Then a cavity with large depth-to-width ratio called keyhole was formed in the weld pool under the dynamical interaction of laser irradiation, plasma arc and filler droplets. An externally supplied shielding gas provides the protection of molten metal from exposing to the atmosphere. The successive weld pools create a weld bead and become a part of a welded joint when solidified. The numbers of process parameters are greatly increased in the hybrid welding, mainly including laser beam parameters, electric power parameters, laser-arc interval, electrode diameter, wire feed speed, welding speed and shielding gas. Bagger and Olsen[66] reviewed the fundamental phenomena occurring in laser-arc hybrid welding and the principles for choosing the process parameters. Ribic *et al.*[67] reviewed the recent advances in hybrid welding with emphases on the physical interactions between laser and arc, and the effects of the combined laser-arc heat source on the welding process.

Current understanding of hybrid laser-arc welding is primarily based on experimental observations. Hybrid laser-arc welding is restricted to specific applications, predominantly the joining of thick section plain carbon steels. In order to expand the applications of this joining technique and optimize the processes for its current applications, fundamental understanding of the transport phenomena and the role of each parameter becomes critical. Numerical investigations were often carried out for this purpose. Ribic *et al.*[67] developed a three-dimensional heat transfer and fluid flow model for laser-GTA hybrid welding to understand the temperature field, cooling rates and mixing in the weld pool. Kong and Kovacevic[68] developed a three-dimensional model to simulate the temperature field and thermally induced stress field in the workpiece during the hybrid laser-GTA process. Mathematical models have also been developed to simulate the weld pool formation and flow patterns in hybrid laser-GMA welding by incorporating free surfaces based on the VOF method. Generally, the typical phenomena in GMA welding such as droplets impingement into the weld pool, electromagnetic force in the weld pool and the typical phenomena in laser beaming welding such as keyhole dynamics, inverse Bremsstrahlung absorption and Fresnel absorption were considered in these models. Surface tension, buoyancy, droplet impact force and recoil pressure were considered to calculate the melt flow patterns. In the following, fundamental physics, especially transport phenomena involved in hybrid laser-arc welding will be elaborated.

2. Fundamentals of hybrid laser-arc welding

Since hybrid laser-arc welding involves laser welding, arc welding and their interactions as well, complicated physical processes like metal melting and solidification; melt flow; keyhole plasma formation; arc plasma formation and convection are typically involved, which results in very complex transport phenomena in this welding process[40]. As known,