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Effect of double-pulsed gas metal arc welding (DP-GMAW) process variables on microstructural constituents and hardness of low carbon steel weld deposits

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ABSTRACT

In this study, a bead on plate welding on a low carbon steel plate at different parameter combinations in double-pulsed gas metal arc welding (DP-GMAW) process has been carried out. The effect of heat input, pulse frequency and thermal pulse frequency on solidification variables and microstructure of the weld metal have been thoroughly studied. Formation of inclusion and acicular ferrite during solidification has been calculated to observe the effect of process parameters on the microstructural constituents. Furthermore, the microhardness analysis of the weld metals has been carried out to evaluate the effect of microstructural variations on the property. Several linear and non-linear equations have also been developed to predict the responses as a function of different process variables. The results indicate that decrease in heat input, pulse frequency and thermal pulse frequency increases the volume fraction of inclusion and acicular ferrite in the weld metals. The higher volume fraction of acicular ferrite ultimately results in fine grain microstructure with the higher hardness of weld metals. On the other hand, the grain size of coarse grain heat affected zone (CGHAZ) at lower heat input was finer which ultimately increases the heat affected zone hardness.

1. Introduction

In modern manufacturing industries, arc welding is considered as a major joining process. Among the various types of arc welding, pulsed gas metal arc welding (GMAW-P) is increasingly used for joining a wide variety of ferrous materials in industries due to its inherent advantages such as deep penetration, smooth weld bead, high welding speed, large metal deposition rate, lower spatter, lower distortion and shrinkage, and lesser probability of porosity and fusion defects [1,2]. In pulsed GMAW process, the welding current is pulsed between peak and background period so that it brings the weld zone to the melting point during the peak current period and allows the molten weld pool to cool and solidify during the background current period. The primary parameters of a current pulse are peak current (I_p), background current (I_b), peak current duration (t_p), background current duration (t_b), and pulse frequency (f), as shown in Fig. 1 [3]. Other process parameters such as welding speed, welding voltage, wire feed rate, electrode extension and torch angle, also influence the process behavior and the weld bead shape during GMAW-P welding [4]. In GMAW-P, the droplet transfer is usually controlled in "one drop per pulse" (ODPP), which makes it possible to improve the stability of welding process and the quality of the weld joint [5]. However, the range of the peak current duration for generating ODPP is narrow. If the duration of the peak-current period is longer, multiple drops may be detached in a single pulse. Or, if the duration is shorter, one droplet in multiple pulses (ODMP) may occur. To overcome such uncertainty of ODPP in conventional GMAW-P, Zhang et al. [6] have proposed a modified GMAW-P power source with an active metal transfer control. In this process, a pulse cycle is divided into growth period and detachment period. The growth period is designed based on the desired average current and is below the transition current. After growth period, current is suddenly switched to the base current and the process enters the detachment period which causes the droplet to oscillate vertically. When the droplet moves down, the current is switched back to the peak level. The frequent change in current

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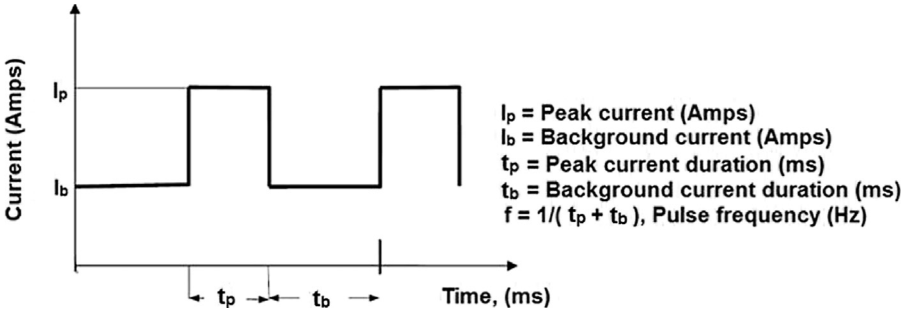

Fig. 1. Pulsed GTAW process parameters [3].

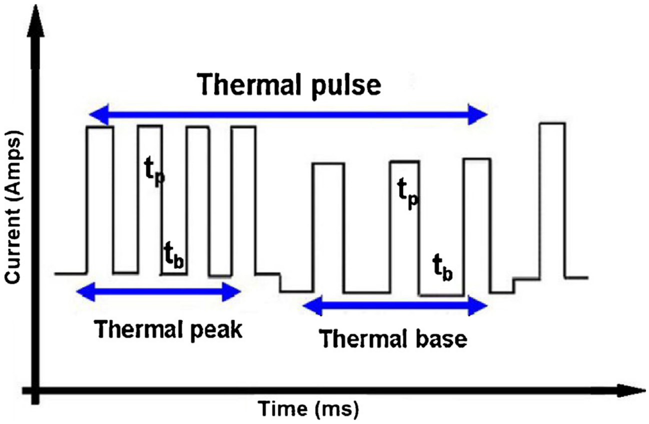

Fig. 2. A schematic diagram of DP-GMAW electrical waveform [10].

incorporates high electromagnetic force and downward momentum which results in ODPP droplet detachment. Xiao et al. [7–9] further modified the original multi-pulse waveform of active metal transfer mechanism by incorporating a longer base period after the exciting pulse known as "active droplet oscillation method" and detaching phase delay period known as "enhanced active metal transfer" to maximize the oscillation and detachment efficiency of the molten droplets. These advanced metal transfer mechanisms are using multiple active pulses within a pulse cycle to achieve easy control on the droplet characteristics of ODPP mode of metal transfer compare to conventional GMAW-P process.

Recently, Liu et al. [10,11] and Mendes da Silva et al. [12] explored the double pulsed GMAW (DP-GMAW) process for aluminium alloys, where a low-frequency current pulsation or the thermal pulse is superimposed on a pulsed current for active metal transfer control and weld pool stirring. The main feature of the DP-GMAW is the simultaneous use of a high-frequency pulse (HFP) and thermal pulse (f_t). The schematic of DP-GMAW waveform is shown in Fig. 2 [10]. The pulse frequency, peak and base value of HFP are cyclically varied with thermal pulse fluctuation. The role of the HFP is to maintain the arc stability and the droplet transfer behavior especially to ensure one droplet transfer per pulse (ODPP) during the welding operation. The thermal pulse (i.e. low-frequency pulse) is used to modulate duration of the high-frequency pulses to improve the weld pool stirring, which guarantees forming of the weld bead ripple and expanding the range of weld joint root gap [11]. An effective fusion of the parent metal and a good weld joint with regular ripple surface can be obtained with the DP-GMAW process [12]. Comparative analysis between DP-GMAW, GMAW-P and conventional GMAW processes have pointed out that the DP-GMAW process has some advantages over other two processes as follows: (a) wider adjusting range; (b) capability to all position welding; (c) wider root gap configuration; (d) reduce overall heat input; (e) improve joint properties; (f) strong weld pool stirring and (g) reduce crack sensitivity. Further details on the DP-GMAW process have been provided in Ref. [13].

Again, the welding process and parameters play a decisive role in controlling the microstructure and mechanical properties of weldments. The present trend in the fabrication industries is the use of automated welding processes to obtain high production rates and high precision. To automate a welding process it is essential to establish the relationship between process variables and weld properties to predict and control desired weld quality [14]. Weld properties include the microstructural constituents like inclusion, phase fraction and grain size along with mechanical properties such as hardness, strength and toughness. These weld properties are sensitive to the welding processes and several input variables. The determination of the direct relationship between welding parameters and weld properties often becomes complex since a number of factors are involved [15].

Previously, microstructural constituents such as inclusion size, inclusion density, grain size and phase fraction (particularly acicular ferrite) along with mechanical properties of different low carbon steel weld metals have been correlated with several factors like heat input, composition, dilution etc. [16–20]. It was reported that the overall microstructure of the C-Mn steel weld metals, in SAW process, changed from martensite to upper bainite to acicular ferrite as the heat input increases from 0.74 to 10 kJ mm^{-1} [16]. However, for high strength low alloy (HSLA) steel weld metals, microstructure changed from coarse polygonal ferrite to acicular ferrite and upper bainite with the increase in the cooling rate from 0.5 to 15 °C/s. The microstructural constituents have decisive role on determination of the weld metal fracture toughness. High fracture toughness is mostly associated with a fine acicular ferrite structure and low inclusion content [21,22]. Poor toughness results from a high proportion of coarse upper bainite. It was also reported that low toughness of weld metals is the resultant of the large and coarse microconstituents (particularly inclusion size). Toughness was enhanced if the particles were fine and uniformly distributed across the weld metals [16]. Liu and Olson [18] also found that an optimum inclusion size distribution is necessary to obtain a large volume fraction of acicular ferrite. Their results indicate that the combination of large austenite grains and high intragranular inclusion density is the key to obtaining a refined microstructure. Weld metal microstructure of microalloyed steel is also affected by the base metal dilution in SAW process. High dilution welds resulted in microstructures that ranged from ferrite with aligned second phase to acicular ferrite depending on the variation of heat input [17]. The compositional effect (particularly carbon and manganese content) is also another factor which controls the microstructural constituents and thus the mechanical properties of weld metals. High levels of acicular ferrite could be achieved with different combinations of carbon and manganese which significantly improves the weld metals toughness [20]. Another study shows the effect of varying heat input on the microstructure and