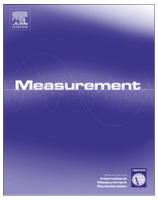
Measurement 70 (2015) 75–82

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement



Effect of welding heat input to metal droplet transfer characterized by structure-borne acoustic emission signals detected in GMAW

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 19 March 2015
Accepted 24 March 2015
Available online 6 April 2015

Keywords:
GMAW
Metal droplet transfer
Acoustic emission
Power spectrum
Energy gradient

ABSTRACT

The structure-borne acoustic emission (AE) signals during gas metal arc welding (GMAW) on 2024 aluminum alloy were detected in real-time and analyzed to find the characteristics of metal droplet transfer (MDT) in welding process. The analysis of time domain and frequency domain was introduced. The energy gradient was used to describe the rate of energy variation during the metal droplet transfer. The results showed that the MDT event of AE signals reflects a mass of transient information about metal droplet transfer in GMAW process. The MDT frequency and the average grain size were increased along with the raise of welding heat input. The increasing welding heat input raised the MDT frequency and the energy input by the metal droplet transferred into the molten pool. According to the energy gradient, the process of short-circuiting transfer of metal droplet was comprised of three parts. The energy gradient and energy transfer coming from the metal droplet transfer were increased along with the welding heat input raised in GMAW process. Therefore, it is possible to study the metal droplet transfer of GMAW by the analysis to the AE signals detected in welding.

1. Introduction

Gas metal arc welding (GMAW) is widely used in manufacturing due to its high deposition efficiency and automatable equipment with better welding quality. The metal droplet transfer (MDT) and its stability are closely associated with the stability of welding process and weld quality. The welding parameters affect the MDT mode as well as the weld quality in GMAW [1,2].

Nakamura et al. used a high speed video camera system to achieve a stable metal inert gas (MIG) welding process [3]. The observation showed that the unstable welding behavior was due to the instability of a column of metal droplet generated at the wire tip. In order to promote the stability of MDT, some researchers have studied the mode and characteristics of MDT. Danut et al. reviewed the metal droplet transfer according to the progress made in the welding sources and techniques development, and proposed a new classification of metal droplet transfer in GMAW. It was extremely important for all the specialists to have know how about the metal droplet transfer and its implications on the process and weld parameters [4]. Luo et al. proposed a new welding method called EMS-CO_2 welding, which improved metal droplet transfer

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http://dx.doi.org/10.1016/j.measurement.2015.03.046
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process, increased the stability of metal droplet transfer, and delivered better control of the welding spatter. Meanwhile, this welding method generated welding formation with refined grains, welding seams with uniform microstructure, and welding joints with a higher quality [5]. Ghosh et al. developed an analytical mode to provide a theoretical understanding of the influence of pulse parameters on the behavior of metal droplet transfer and thermal characteristics in pulsed GMAW. The theoretical model may be useful in the control of pulse parameters to achieve desired behaviors of thermal and metal droplet transfer under different conditions of weld fabrication [6].

There are a lot of process factors affecting the welding stability and weld quality in GMAW. Therefore, the real time monitoring and analysis is highly required in modern automated welding environments [7]. Some researchers acquired welding arc sound signals to analyze and correlate them with the metal droplet transfer or the welding stability. Kamal et al. compared the arc sound of pulsed GMAW at various process parameters. The arc sound was found to be strongly related to both metal droplet transfer and weld quality. The arc sound was also used to detect the welding stability and welding defects [8]. Saad et al. investigated the relationships between the acoustic signal and the modes of the welding pool in variable polarity plasma arc welding. Welch power spectral density (PSD) estimate and a neural network (NN) were used to distinguish the keyhole mode on the basis of acoustic signals analysis. The results showed that the keyhole mode can be distinguished from the cutting mode under the experiment conditions [9]. Kamal et al. used the sound sensor and other sensors to properly monitor the depth of weld penetration. The various pulse parameters were varied to investigate their influence on weld penetration in pulsed GMAW. Finally, the weld penetration monitoring was found be better with the arc sound kurtosis [10].

In this study, according to the structure-borne acoustic emission (AE) signals detected in GMAW on aluminum alloy, the analysis of time domain and frequency domain were introduced, and the energy gradient was used to analyze the characteristics of metal droplet transfer.

Table 1
Welding parameters used in welding experiment.

No.	Welding current I/A	Arc voltage U/V	Welding speed v/m min^{-1}	Heat input Q/J mm^{-1}
A01	79	15.0	0.32	222
A02	120	16.2	0.32	365
A03	150	16.4	0.32	461

2. Experiment details

The materials used in experiment were 2024 aluminum alloys of 4 mm thin sheets and ER4043 aluminum welding wire of 1.2 mm diameter. DC GMAW machine was used to weld 2024 aluminum alloy. Welding parameters used in welding experiment were shown in Table 1. It can be seen that different welding heat input values were achieved by the change of welding current or arc voltage. The welding current and arc voltage correlate closely to the transfer mode of metal droplet. Conventional transfer modes include short-circuiting mode, globular mode, spray mode and streaming mode [4]. The transfer mode of metal droplet is short-circuiting transfer mode by the welding parameters in Table 1.

As welding arc affects molten pool in GMAW, acoustic emission (AE) signals are released. The AE signals in welding process were monitored in real-time, which can be detected by the piezoelectric sensor mounted on the workpiece. So, it was called structure-borne sensing. As the workpiece is used as transmission medium, the losses of AE signals during welding process are less. The diagram of experimental equipments was shown in Fig. 1. The harmonic frequency of piezoelectric sensor used in experiment was 150 kHz. The piezoelectric sensor was fixed on the workpiece as shown in Fig. 1. Considering the thermal conduction in workpiece, the couplant used in experiment was characterized with high-temperature resistance. Obviously, the workpiece also was the intermediate for acoustic emission transmission, which was called structure-borne mode. The AE signals detected in experiment were called structure-borne AE signals. In comparison with air-borne mode, the structure-borne mode has less

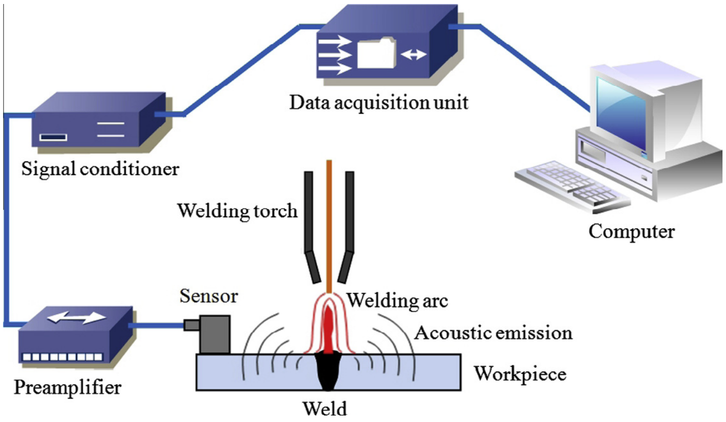


Fig. 1. Schematic diagram showing experimental equipment.

surrounding noises affecting the main signals. The AE signals detected during welding process were amplified by the preamplifier, processed by the signal conditioner and transferred to the computer by data acquisition unit for further processing and analysis.

3. Experiment results

Welding arc is characterized with thermal-effect and impact force effect. The heat energy and impact force needed by welding is transferred to molten pool by the welding arc during GMAW. In this process, various physic effects, including arc effect, electromagnetic effect, vibration effect, etc, are taken place with energy released. These physic effects relates to the welding process. Particularly, as the metal droplets are transferred into the molten pool in various transfer modes, the thermal-effect and impact force effect are transferred synchronously. This process can produce thermoelastic wave. Accordingly, AE energy is released during welding process. The AE signals detected in GMAW indicate the characteristics of AE energy and metal droplet transfer.

Fig. 2 showed the weld appearance of GMAW for 2024 aluminum alloy and the AE signals corresponding to welding process. It can be seen that there was a mapping relation between the process of the weld formation and the waves of AE signals. In order to analyze the details of AE signals of welding process, the area A in AE signals was amplified to show in Fig. 3. It was clearly that the waves of AE signals detected in welding were composed of several AE events. The AE event comes from the impact effect of the metal droplet transferred to molten pool. So, the AE event is called metal droplet transfer event (MDT event). Obviously, the MDT event reflects a mass of transient information about metal droplet transfer. The cycle (T) of MDT event was just the cycle of the metal droplet transfer. Accordingly, it was possible to study the metal droplet transfer of GMAW by the analysis to the AE signals detected in welding.

Fig. 4 showed the waves of AE signals detected in GMAW at different welding parameters. From specimen A01 to A03, the welding heat input increased from 222 J/mm to 461 J/mm along with the welding parameters change. The duration of detection process was 2.5 s. The amount of MDT events increased along with the raise of welding heat input in 2.5 s, which indicated the variation of MDT frequency according to the change of welding heat input. The quantity of metal droplets transferred into molten pool in unit time was called MDT frequency. Fig. 5 showed the variation tendency of MDT frequency affected by welding heat input. The MDT frequency increased from 14 Hz to 40 Hz along with the raise of welding heat input. Accordingly, it can be inferred that the volume of metal droplet transferred into molten pool was reduced. So, the welding heat input contributes to the metal droplet transfer in GMAW.

In addition, Fig. 6 showed the influence of the welding heat input on the microstructure of the weld metal. There was a visible tendency of grain growth coarsening

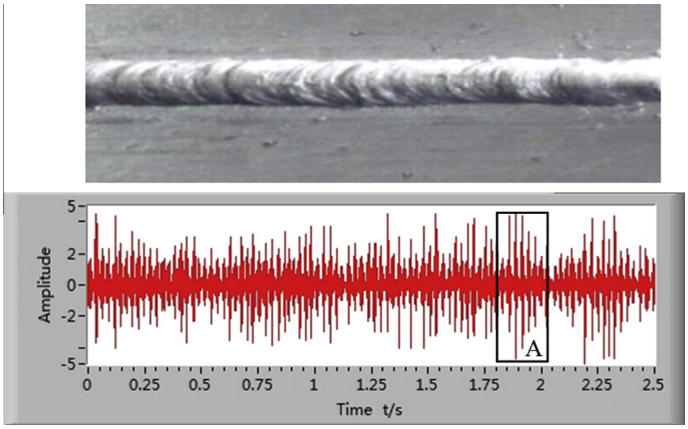


Fig. 2. AE signals detected in GMAW welding.

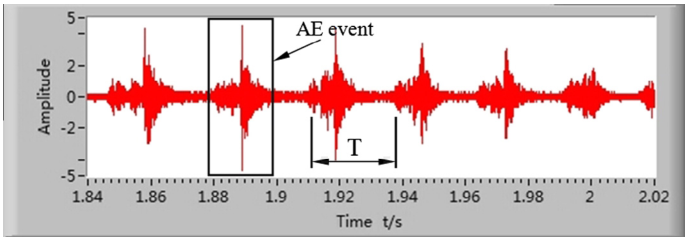
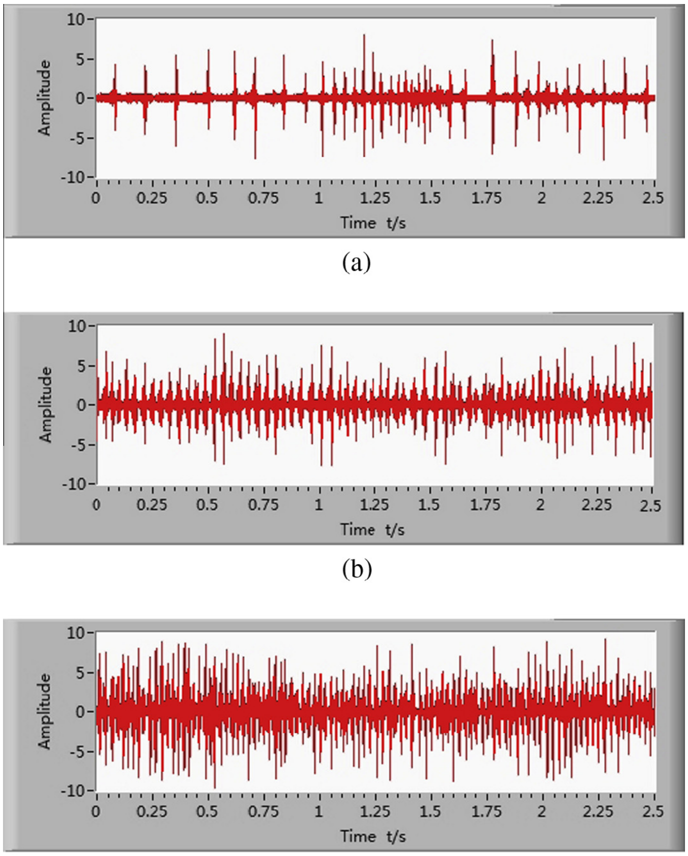


Fig. 3. AE event of metal droplet transfer in GMAW welding.



(a)

(b)

(c)

Fig. 4. AE signals detected in GMAW welding at different welding parameters. (a) A01: $Q = 222\ \mathrm{J\ mm^{-1}}$, (b) A02: $Q = 365\ \mathrm{J\ mm^{-1}}$ and (c) A03: $Q = 461\ \mathrm{J\ mm^{-1}}$.

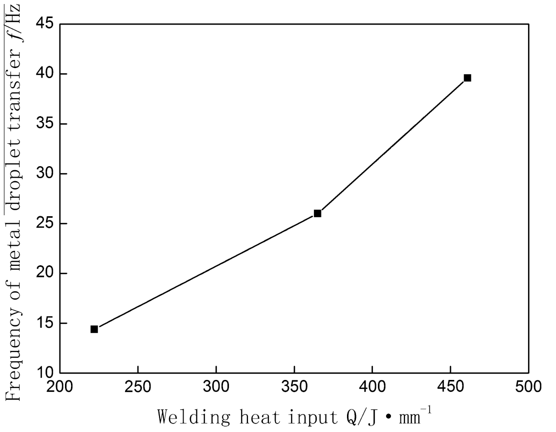


Fig. 5. Frequency of metal droplet transfer affected by welding heat input.

as the welding heat input increasing. The average grain size grew from 5.1 um to 23.5 um along with the raise of welding heat input, as shown in Fig. 7. Of course, the change of welding heat input is depended on the welding parameters, such as welding current, arc voltage and welding speed. It also showed that the influence of welding parameters on the metal droplet transfer or the microstructure of weld metal can be characterized by welding heat input.

4. Discussion

4.1. Power spectrum analysis of AE signals

In order to study the energy characteristics of metal droplet transfer, power spectrum was used to analyze the AE signals detected in GMAW. Fig. 8 showed the results of power spectrum analysis of AE signals in Fig. 4. Because of the welding heat input variation, the distribution of power spectrum of AE signals for metal droplet transfer was different. But there was a wide distribution for the frequency domain, which frequency ranges were distributed from 2 k to 55 kHz as shown in Fig. 8 and which was the common trait of AE signals of metal droplet transfer. As the welding heat input was small, the MDT frequency and the energy input by the metal droplet transferred into the molten pool were less. So, the peak

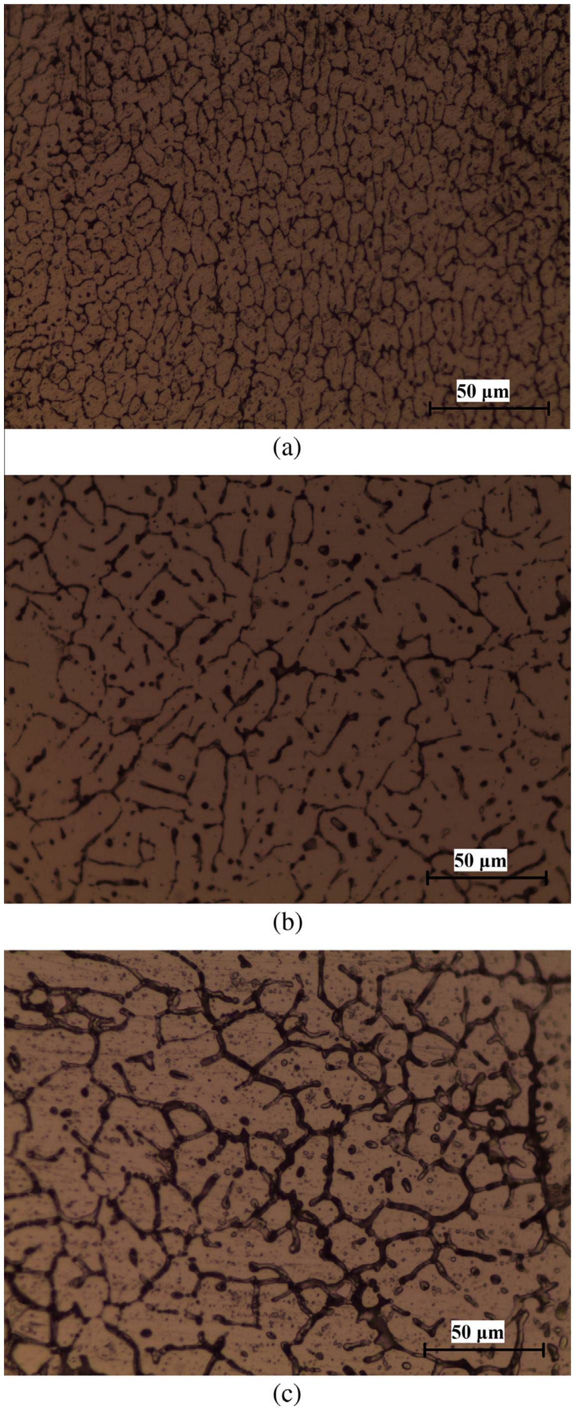


Fig. 6. Optical micrographs showing influence of the welding heat input on the microstructure of the weld metal. (a) A01: $Q = 222\,\text{J mm}^{-1}$, (b) A02: $Q = 365\,\text{J mm}^{-1}$ and (c) A03: $Q = 461\,\text{J mm}^{-1}$.

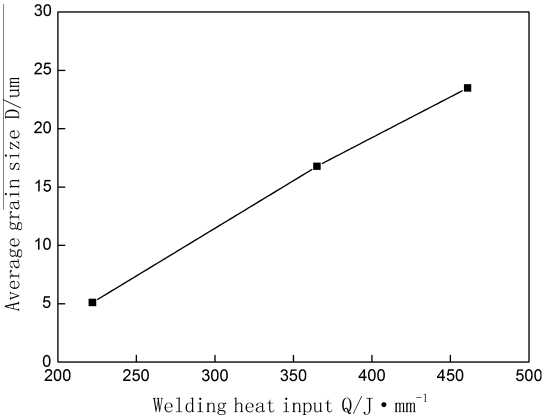


Fig. 7. Influence of the welding heat input on the average grain size of the weld metal.

value of power spectrum of AE signals was small (Fig. 8a). After the welding heat input was increased, the peak value of power spectrum of AE signals was raised evidently (Fig. 8b and c). There were distinctive energy peaks not only in low frequency domain but also in high frequency domain. This phenomenon indicated that the increasing welding heat input raised the MDT frequency and the energy input by the metal droplet transferred into the molten pool. In order to study the energy input by the metal droplet transfer, the energy gradient was proposed in following study.

4.2. Analysis of energy gradient for metal droplet transfer

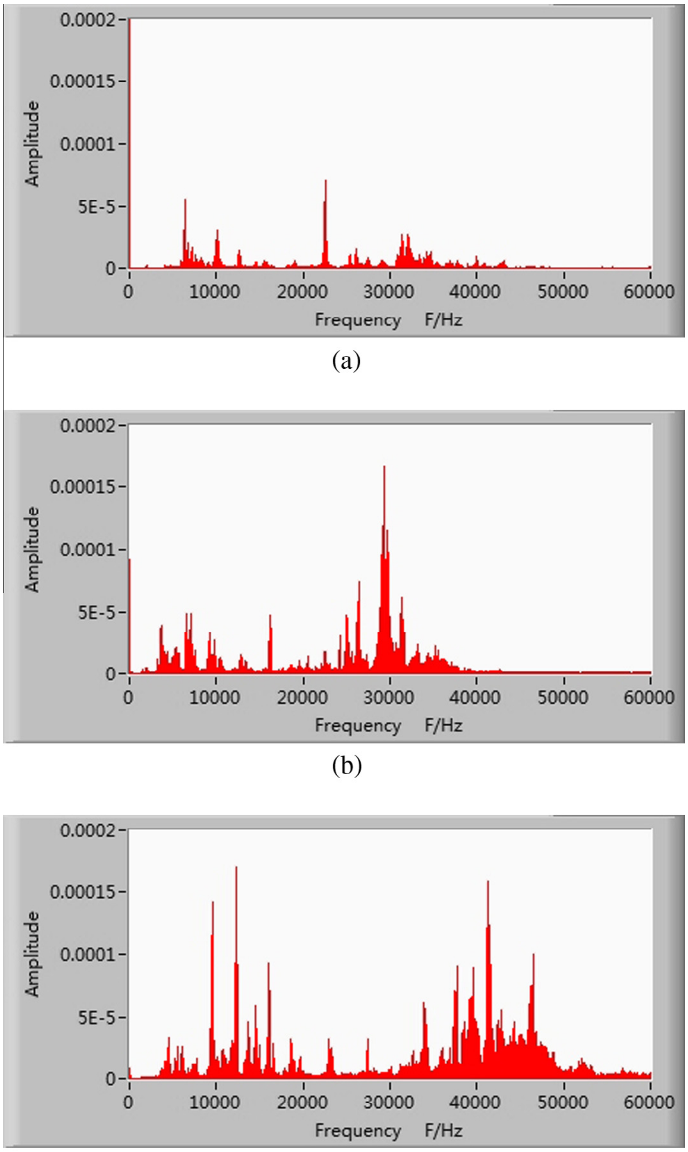
The energy gradient was used to describe the rate of energy variation during the metal droplet transfer in this study. We used $U_{ms}(t)$ as the symbol for energy gradient, which was defined as

$$U_{ms}(t) = \frac{\int_{t_1}^{t_2} U^2(t)dt}{t_2 - t_1} \tag{1}$$

where $U(t)$ is the AE signal voltage varying with time.

The welding parameters as shown in Table 1 fall into the interval of short-circuiting transfer mode [3]. The AE signals waves of metal droplet transfer showed a characteristics of short-circuiting transfer. We divided the AE signals waves into three parts, as shown in Fig. 9. The AE signals waves of three parts correspond to various phases of metal droplet transfer. In part I of AE signals waves, the welding arc melts the welding wire to form metal droplet, but the metal droplet does not touch with molten pool. As the metal droplet grows to touch the molten pool and gradually forms necking phenomenon, the process falls into part II of AE signals waves. As the necking metal disconnects the tip of welding wire and the metal droplet transfers to spread out in the molten pool, the process falls into part III of AE signals waves. This process turns to recur at periodic intervals of metal droplet transfer.

The energy gradient also was shown in Fig. 9. These three processes of short-circuiting transfer showed different characteristics of energy gradient. As the process falls into part I, the energy gradient is smooth. Because the metal droplet is in the forming process and there is no any transfer, the energy transfer coming from metal droplet is less and smooth. As the process falls into part II, the energy gradient is higher than part I, which is attributable to the metal droplet touching the molten pool and



(a)

(b)

(c)

Fig. 8. Power spectrum analysis of AE signals detected in GMAW welding. (a) A01: $Q = 222\ \mathrm{J\ mm^{-1}}$, (b) A02: $Q = 365\ \mathrm{J\ mm^{-1}}$ and (c) A03: $Q = 461\ \mathrm{J\ mm^{-1}}$.

forming necking promotes the energy transferred to molten pool. As the process falls into part III, the metal droplet transfers into the molten pool and impacts the molten pool, which brings most of energy transfer. So, the energy gradient of this part is highest. Accordingly, the area included in the curve of energy gradient indicates the amount of energy transfer coming from the metal droplet transfer.

Fig. 10 showed the AE signals of only one metal droplet transfer taken from welding processes with different welding heat input. The waves of AE signals was different as the welding heat input and the metal droplet transfer were various, which had been talked about in above paragraphs. Fig. 11 showed the energy gradient of only one metal droplet transfer at different welding heat input for AE signals in Fig. 10. It was clearly that the energy gradient was highest as the welding heat input was 461 J/mm. Conversely, the energy gradient was lowest as the welding heat input was 222 J/mm. According to the area included in the curve of energy gradient, it can be seen that the energy transfer coming from the metal droplet transfer was highest as the welding heat input was 461 J/mm, which was higher than the energy transfer as the welding input was 222 J/mm or 365 J/mm. Therefore, the welding heat input not only increases the MDT frequency and the average grain size in weld, but also increases the energy gradient and

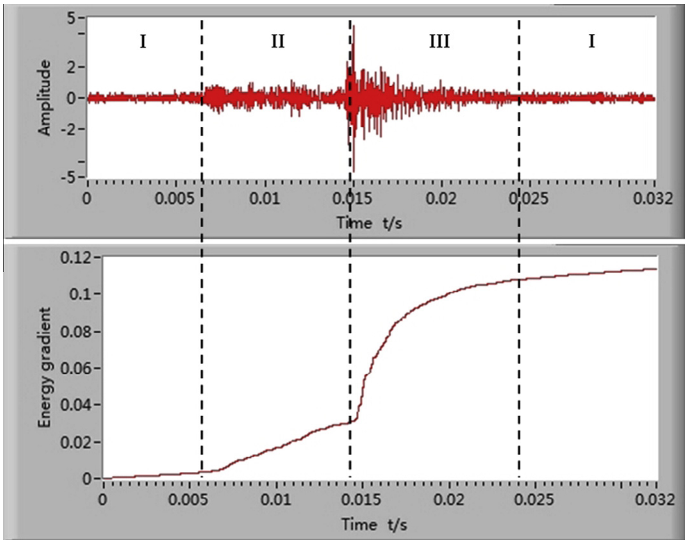


Fig. 9. Energy gradient of AE signals for metal droplet transfer.

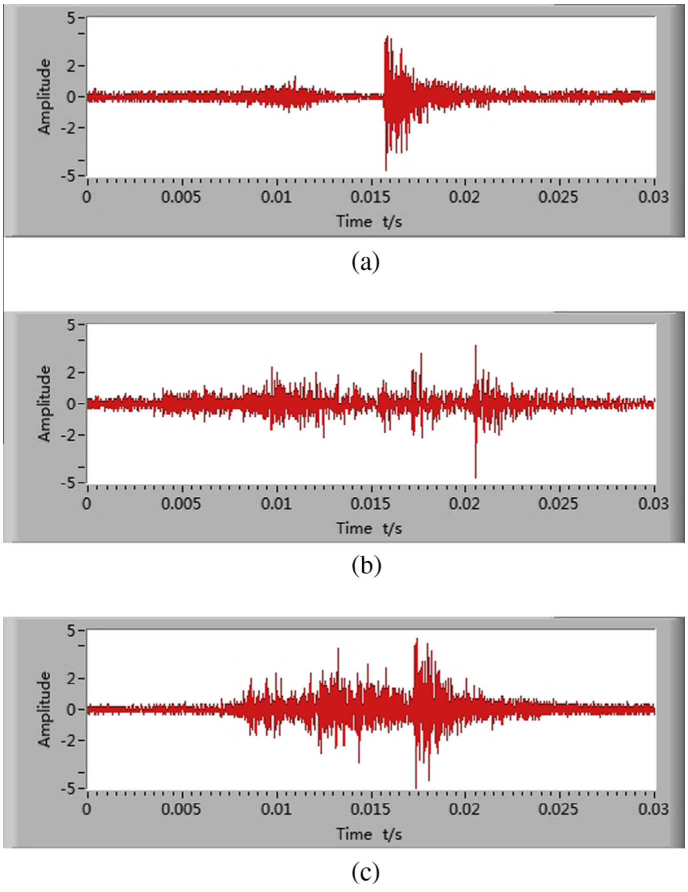


Fig. 10. AE signals of only one metal droplet transfer taken from AE signals in Fig.4. (a) A01: $Q = 222\ \mathrm{J\ mm^{-1}}$, (b) A02: $Q = 365\ \mathrm{J\ mm^{-1}}$ and (c) A03: $Q = 461\ \mathrm{J\ mm^{-1}}$.

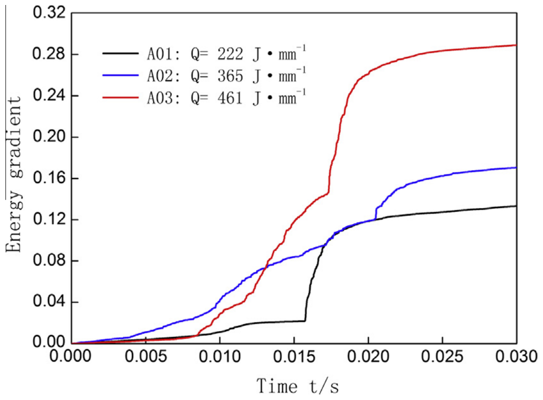


Fig. 11. Energy gradient of AE signals of only one metal droplet transfer at different welding heat input.

the energy transferred into molten pool by the metal droplet in GMAW process.

5. Conclusions

(1) The MDT event reflects a mass of transient information about metal droplet transfer. It is possible to study the metal droplet transfer of GMAW by the analysis to the AE signals detected in welding. The MDT frequency and the average grain size are increased along with the raise of welding heat input.

(2) The distribution of power spectrum of AE signals for metal droplet transfer was different according to the welding heat input variation. The increasing welding heat input raised the MDT frequency and the energy input by the metal droplet transferred into the molten pool.

(3) The waves of AE signals was different as the welding heat input and the metal droplet transfer were various. According to the energy gradient, the process of short-circuiting transfer of metal droplet was comprised of three parts. The energy gradient and energy transfer coming from the metal droplet transfer were increased along with the welding heat input raised in GMAW process.

Acknowledgements

This work was supported by Scientific and Technological Research Program of Chongqing Municipal Education Commission of China (Grant No. KJ1400930), Chongqing Municipal Engineering Research Center of Institutions of Higher Education for Special Welding Materials and Technology (Grant No. SWMT201504) and the Assistance Scheme for Young Core Teacher of Chongqing Colleges.

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