The Effect of EN Pulsing Ratio and Repetition Frequency on the Bead Appearance and Microstructure Evolution in Aluminum Welding using Variable Polarity GMAW

가변극성을 이용한 알루미늄 GMAW 용접에서 주기 내 EN 펄스 비율 및 반복횟수가 용접부 형상 및 조직형성에 미치는 영향

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Abstract

This study addressed the gas metal arc welding (GMAW) of Al 5183 aluminum alloy using variable polarity (VP). The effects of the electrode negative (EN) pulsing ratio and repetition frequency on the geometrical features and microstructural evolution of the deposited materials were investigated and discussed. The current and voltage were manually controlled independently for each phase to evaluate the effect of the polarity change. The influence of phase and its changing frequency on the geometrical features and microstructure evolution were observed. The phase of the electrode affected the arc concentration and changed the amount of the deposited material and the dilution between the substrate. The EN phase is beneficial for making a finer structure than the electrode positive (EP) phase because of the lower heat input per unit mass. In addition, the size of the grains decreased as the phase change frequency increased. When the number of repetitions frequency increased within a cycle, the size of the microstructure was reduced. Consequently, strategies can be established to minimize the microstructure with VP-GMAW welding using a high EN pulsing ratio and low repetition conditions.

Key Words: Variable polarity, Gas metal arc welding, EN pulsing ratio, Repetition, Microstructure refining, aluminum

1. Introduction

As the demand for low heat input and low deformation arc welding increases, the application of cold metal transfer (CMT) power sources capable of short-circuiting are also increasing. Among them, a welding power source, which can manually apply short-circuiting under variable polarity (VP), can arbitrarily adjust the number of electrode positive (EP) and electrode negative (EN) phase within one cycle. This welding power source can maximize the functions desired by users such as a deposition amount or depth of fusion accord-

ing to the target product.

VP-GMAW power source has attracted attention from researchers because of various arc behavior according to polarity¹⁻⁴⁾. Kumar⁵⁾ and Park⁶⁾ analyzed the arc concentration according to the polarity during AC pulsed GMAW welding and investigated the relationship with the heat input. Kiran⁷⁾ mentioned that the use of AC pulse GMAW was effective in enhancing the gap bridging ability and reducing the deformation. Because the deposition amount increased by the arc concentration occurred on the filler wire. Several researches have also been published to compare microstructure and mechanical properties according to process parameters using

the CMT process. Cong reported that CMT-advanced (Fronius, Austria) was advantageous in reducing porosity when applied to an aluminum alloy of the 2000 series^{8,9)}. Fang^{10,11)} and Cong¹²⁾ claimed that when short-circuiting transfer was applied under variable polarity environment, the equiaxed structure ratio was high and the anisotropy of mechanical properties according to the stacking direction can be overcome during the wire additive manufacturing of aluminum alloy.

In AC pulse welding, the EN ratio is an important factor because it affects the welding characteristics. Numerous researches have been published on the welding droplet transfer and penetration depth depending on the EN ratio^{6,7,13)}. At an AC-GMAW process with a high EN ratio, the arc stability has deteriorated and the droplet transfer was unstable. Thus, the application of the EN pulse has been limited. The use of VP-GMAW power source allows the EN polarity dominant waveform, the influence on the arc instability during the EN cycle can be neglectable. Because it mechanically controls the wire feeding motion during the detaching period. In recent years, it is possible to control the EN ratio and the number of EN pulses in one cycle, which enables a wide range of studies about the EN phase. In this study, the effect of the change in EN pulsing ratio on the bead formation and microstructural evolution by applying the variable polarity process. However, the effect on the application of the EN phase was not clear due to an extreme difference in the waveform of each of the phases. In addition, the effect of the pulse repetition frequency in the cycle was amplified and attenuated, which made difficult to compare.

For the wire additive manufacturing and repair welding process, the amount of deposited weight and thermal distortion of the substrate are important factors to be managed. By applying VP-GMAW, it is possible to establish a strategy to maximize the deposited material or minimize thermal deformation based on the application. In this study, the effects of EN pulsing ratio and pulse repetition frequency on bead appearance and microstructure formation were investigated under the polarity changeable environment.

2. Experimental procedure

Bead-on-plate welding was performed using an Al 5183 wire with a diameter of 1.2 mm on a 16 mm-thick Al 5083 plate. A VP-GMAW machine (Fronius, Austria) was used and the work angle and the travel angle were set to 0° as shown in Fig. 1. The distance between the contact tip and the workpiece was 20 mm, and Ar gas was supplied with a flow rate of 20 l/min.

It is advantageous to synchronize waveforms of EP

Fig. 1 Experimental setup

Contents	Value
(1) Detach current (A)	± 96.0
(2) Base current (A)	± 80.0
(3) Boost up (A/ms)	± 300.0
(4) Tau boost up (ms)	0.1
(5) Peak current (A)	± 244.0
(6) Pulse duration peak (ms)	4.76
(7) Boost down (A/ms)	± 300.0
(8) Tau boost down (ms)	0.2

Fig. 2 Schematic diagram of current waveform

Table 1 Welding conditions applied in the experiment

Variables	Value
Wire feed rate (m/min)	9 (1 level)
Welding speed (m/min)	0.3, 0.5, 0.7 (3 levels)
EN pulsing ratio (EN pulse/Total pulse)	0, 0.1, 0.25, 0.33, 0.5, 0.67, 0.75, 0.9, 1 (9 levels)
Repetition	1, 3, 5 (3 levels)

and EN phases for the comparison of the effect of EN pulsing ratio (R_{EN}) on bead formation and metallurgical features. As shown in Fig. 2, the waveform of each phase; the current and dwell time were artificially matched to minimize the difference in heat input for each polarity. The duty for phase change also varied depending on the number of pulses of EP and EN in a cycle. In this study, EN pulsing ratio was set to 9 levels and the repetition frequency in a cycle was set to 3 levels. For example, where ratios of EP and EN pulsing in a cycle were 1:3 and 3:9, both have the same EN pulsing ratio of 0.75. However, the phase change frequency is three times higher in the case of 1:3. Table 1

shows the detailed welding condition applied in the experiment.

3. Results and Discussion

3.1 Waveform comparison according to the change of the EN pulsing ratio

The droplets formed during the peak current period (Fig. 2 (b)) were transferred to the molten pool by the push-pull motion of the welding torch during the detach current period. Thus, the number of pulses matched the number of drop transfers regardless of EP or EN phases. Measured waveforms depending on the EN pulsing ratio and the repetition frequency are shown in Fig. 3. Short circuits occurred 13-14 times during 200 ms, which was independent of the EN pulsing ratio and repetition frequency. RMS values of current, voltage and heat input according to the EN pulsing ratio was calculated based on the measured waveforms and are given in Fig. 4. The current/voltage and heat input were similar under the condition when the electrode polarity (EP) having the EN pulsing ratio below 0.5 mainly functions. On the other hand, when the EN pulsing ratio was increased to above 0.5, the total heat input tended to decrease as the current value was decreased. However, the effect of the change in welding speed on the current/voltage and supply energy was not confirmed.

The droplet size and the molten pool geometry were changed according to the polarity. In Fig. 5, (a)-(c) show the droplet transfer during EP phase, and (d)-(f) show the droplet transfer during EN phase. Fig. 5 (b), (c) and (e), (f) show the droplet transfer behavior at the peak current and detach current period for EP and EN phases, respectively. Deflection on the surface of the molten pool was observed due to arc pressure in the EP phase (Fig. 5(b)), and relatively large droplets were formed in the EN phase condition.

3.2 Comparison of weldability according to EN pulsing ratio change

Changes in droplet transfer and surface deflection of molten pool affect the penetration depth and the amount of deposition. Bead appearances according to the EN pulsing ratio were given in Fig. 6. The frequency of phase changes increased until the EN pulsing ratio reached 0.5 and then decreased. Frequent phase changes alleviate the ripples on the weld bead. When the repetition frequency was one as shown in Fig. 6(a)-(e), the ripple was obvious compared to the repetition frequency was 3 or 5 as shown in Fig. 6(f)-(i). As the EN pulsing ratio increased, the height and width of the bead tended to increase. In addition, the height and width of the bead were larger in the low welding speed condition than the high welding speed condition (Fig.

Fig. 3 Measured current waveform depending on EN pulsing ratio with (a) one and (b) three times repetition

Fig. 4 Measured (a) welding current, (b) voltage and calculated (c) heat input depending on EN pulsing ratio and welding speed (one repetition condition)

Fig. 5 High-speed camera images captured during the droplet transfer depending on phase. ((a) to (c): EP phase, (d) to (f): EN phase). (a) and (d) represent base current period for each phase, (b) and (e) are peak current, (c) and (f) are images for detach current period

	Repetition	EN pulsing ratio	Bead appearance
(a)	×1	0	
(b)		0.25	
(c)		0.5	
(d)		0.75	
(e)		1	
(f)	×3	0.25	
(g)		0.5	
(h)	×5	0.25	
(i)		0.5	

Fig. 6 Bead appearances under the variable EN pulsing ratio and repetition. The specimen was fabricated with a welding speed of 0.7 m/min

Fig. 7 Bead height and width of deposit materials depending on EN pulsing ratio and welding speed under variable repetition conditions of (a) one and (b) five times

7). Because the increase of the repetition frequency promoted the ripple formation, height and width variations were large in each condition. However, the average height and width of the beads were similar independently of the repetition frequency.

The deposited area was increased with increasing EN pulsing ratio in a cycle (Fig. 8(a)). It is considered that the melting of the filler wire was accelerated under the EN phase. On the other hand, the penetration into the substrate was decreased as the EN pulsing ratio increased. In particular, when the EN pulsing ratio exceeded 0.5, penetration decreased rapidly.

Because the energy transfer to the substrate was limited, and the effect of gravity during the droplet transfer was reduced by applying the short-circuit transfer process. The weight of the droplets tended to increase

Fig. 8 (a) Deposition and dilution area derived from sectional image of the welds, and (b) weight of welds per length of 120 mm depending on EN pulsing ratio and repetition.

proportionally with the EN pulsing ratio and was linearly increased as the repetition frequency increased (Fig. 8(b)). Therefore, it was confirmed that more deposited materials were stacked in the unit weld length at the 0.5 EN pulsing ratio condition where the phase changes frequently. It was predicted as a temporary phenomenon that appeared when the power source controlled the current to stabilize the arc during the polarity change.

3.3 Effects of EN pulsing ratio change on structure formation

The change in EN pulsing ratio affects dilution of the substrate, and the nucleation site may differ due to the flow inside the molten pool by the polarity change^{14,15}. The microstructural constitution of the welds can be varied by numerous factors such as chemical composition, impurities, and welding parameters. The cooling rate is the correlation between the temperature gradient and the solidification rate. It is usually determined by the

welding speed and heat input. If the cooling rate is fast, a finer structure can be formed¹⁶⁾.

The temperature was measured during the process with a thermocouple attached 11 mm below the upper specimen. As shown in Fig. 9, the maximum temperature and cooling rate were measured at the EN pulsing ratio of 0.5 when the phase change frequency was the highest. The lowest values were obtained when EN or EP polarity was used alone. Even with the same phase change frequency, the measured temperature was different according to the EN pulsing ratio in a cycle. This trend conflicted with the heat input derived from the measured waveforms in Fig. 4. Therefore, it is inferred that the efficiency and function can be different depending on the polarity.

The change of the microstructure according to the EN pulsing ratio was investigated and presented in Fig. 10. Babu¹⁷⁾ mentioned that the polarity change during pulse welding could suppress the grain growth because it affected the flow fluctuation inside the molten pool. When the EN pulsing ratio is between 0 and 0.5, the formation of the equiaxed structure was more dominant than the columnar structure as the EN pulsing ratio increasing. At a low phase change frequency (0-0.25), epitaxial growth, a symbol of anisotropy growth, was observed in the direction of the heat source.

On the other hand, it is presumed that most of the energy was mainly consumed to melt the wire at the EN polarity 100 % condition. Because the droplet temperature is lower than the EP phase period, finer grain can be obtained.

4. Conclusion

In this study, the effect of the EN pulsing ratio and the

(a)

(b)

Fig. 9 (a) Measured temperature and (b) calculated cooling rate depending on EN pulsing ratio. Welding speed and repetition were fixed at 0.5 m/min and three times, respectively

Repetition	EN pulsing ratio				
	0 (EP only)	0.25	0.5	0.75	1
×1
×3	-				-

Fig. 10 Microstructure in longitudinal direction depending on EN pulsing ratio and repetition

repetition frequency on the bead appearance and microstructure was investigated using a short-circuiting mode VP-GMAW power source and the following conclusions were drawn.

1) EN pulsing ratio change directly affects the arc concentration location, which caused a change in the amount of deposition and melting of the substrate. The droplet size was small, and the surface of the molten pool was deflected due to strong arc generation in the EP phase period. While the droplet size was large even though low input energy was supplied in the EN phase, and the arc was formed at a relatively high position compared to the EP phase period. As the EN pulsing ratio increased, the weight of the deposition tended to increase, and width tended to increase. As the repetition frequency in a cycle was increased, the ripple on the weld bead was clearly observed, but the effect of repetition frequency on the weight of the droplet was negligible.

2) The effect of phase and polarity changing frequency on microstructure formation was confirmed. It is inferred that it is possible to form a fine structure under EN polarity compared to EP polarity. Because not only relatively low heat input was supplied under the condition of high EN pulsing ratio, but also because the temperature of the droplet was low due to the large amount of energy consumed to melt the wire. Epitaxial growth was observed due to the thermal overlap of the applied heat input at a low EN pulsing ratio. It was reconfirmed that anisotropic characteristics can be suppressed through the phase change, similar to the research of Fang¹¹⁾ and Cong¹²⁾. As the frequency of phase change increased, the size of the grains decreased. When the repetition frequency in a cycle increased, the frequency of phase changes decreased. Thus, it is considered to be advantageous to reduce the repetition frequency to reduce the grain size.

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가변극성을 이용한 알루미늄 GMAW 용접에서 주기 내 EN 펄스 비율 및 반복횟수가 용접부 형상 및 조직형성에 미치는 영향

The Effect of EN Pulsing Ratio and Repetition Frequency on the Bead Appearance and Microstructure Evolution in Aluminum Welding using Variable Polarity GMAW

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1. 서 론

저입열, 저변형 아크용접 수요가 증가함에 따라 강제 단락이행을 하는 CMT(cold metal transfer) 전원의 적용 또한 증가하고 있다. 그 중 가변극성과 동시에 단락이행을 적용할 수 있는 용접전원의 경우, 제어를 통해 하나의 주기내 양극과 음극 파형의 개수를 임의로 조절하는 것이 가능하다. 해당 용접전원은 대상 제품에 맞추어 용착량 또는 용입깊이 등 사용자가 원하는 기능을 극대화 할 수 있다는 특징을 가지고 있다.

가변극성 용접전원은 극성에 따라 아크 편향이 발생되기 때문에 연구자들의 관심을 받아왔다¹⁻⁴⁾. Kumar⁵⁾과 Park⁶⁾은 AC pulsed GMAW 용접 중 극성의 방향에 따른 아크의 집중을 분석하고 입열량과의 관계에 대해 고찰하였으며, Kiran⁷⁾은 AC 펄스 GMAW를 활용하는 경우 와이어에 아크 집중이 발생하여 용착량이 증가하기 때문에 갭 브리지 및 변형 저감등에 효과적이라고 언급하였다. CMT 프로세스를 활용하여 공정변수에 따른 조직 및 기계적 물성을 비교하는 연구결과 또한 다수 발표되었다. Cong은 알루미늄 2천계열을 대상으로 CMT-advanced(CMT-adv.)를 적용하고 내부기공 저감에 유리하다고 발표하였다^{8,9)}. Fang^{10,11)} 및 Cong¹²⁾은 알루미늄을 대상으로 단락이행 모드를 활용하여 와이어 적층을 실시하고, 가변극성을 적용하는 경우에서 등축정의 비율이 높고 적층 방향에 따른 기계적 물성의 이방성이 적다고 주장하였다.

AC 펄스 용접에서 역극성 (Electrode negative, EN) 비율은 용접특성에 영향을 미치기 때문에 중요하게 다루어진다. 다수의 연구자에 의해 EN 비율에 따른 용적의 이행 및 용입깊이 등에 대해 연구 결과가 발표된 바 있다^{6,7,13)}. 그러나 AC-GMAW 공정의 경우 높

은 EN 비율에서 아크 안정성 저하되고 용적이행이 불안하여 역극성의 적용이 제한적이었다. 가변극성 단락이행 용접전원을 사용하는 경우 기계적으로 단락모드를 제어하기 때문에 EN 주기에서 아크의 불안정성에 대한 영향이 상대적으로 적다. 최근에는 EN 비율뿐만 아니라 주기 내의 EN 펄스의 수 또한 제어하는 것이 가능하여 역극성에 대한 폭넓은 연구가 가능해졌다. 저자는 가변극성 공정을 적용하여 EN 비율의 변화가 비드형성 및 미세조직 구성에 미치는 영향을 고찰한 바 있다. 그러나 극성에 따른 파형의 차이가 극심하여 역극성 적용에 대한 효과가 명료하지 않았다. 또한 주기 내 펄스 반복횟수가 미치는 영향이 증폭/상쇄되어 비교가 어려웠다.

적층 및 보수 용접에 있어서 용착량 및 부재에 가해지는 열변형 등은 매우 중요한 요인으로 작용할 수 있다. 가변극성을 적용하는 경우, 적용처에 맞추어 용착량 극대화하거나 열변형을 최소화하는 전략이 수립가능하다. 해당연구에서는 가변극성 단락이행 공정을 활용하여 한 주기 내 EN 펄스 비율 및 펄스 반복횟수의 변화가 비드형성 및 미세조직 구성에 미치는 영향을 분석하고 고찰하고자 하였다.

2. 실험방법

아크 용접은 16 mm 두께의 Al 5083 판재위에 1.2 mm 직경의 Al 5183 와이어를 사용하여 비드용접의 형태로 진행하였다. 가변극성을 부여하기 위해 오스트리아 Fronius社の 가변극성 단락이행 용접기를 사용하였으며, Fig. 1과 같이 작업각 및 진행각은 0°가 되도록 설치하였다. 컨택트 팁과 부재간의 거리는 20 mm으로 설정하였으며, Ar 20 l/min를 송급하였다.

EN 비율이 비드형성 및 조직구성에 미치는 영향을

Fig. 1 Experimental setup

Contents	Value
(1) Detach current (A)	± 96.0
(2) Base current (A)	± 80.0
(3) Boost up (A/ms)	± 300.0
(4) Tau boost up (ms)	0.1
(5) Peak current (A)	± 244.0
(6) Pulse duration peak (ms)	4.76
(7) Boost down (A/ms)	± 300.0
(8) Tau boost down (ms)	0.2

Fig. 2 Schematic diagram of current waveform

상대 비교하기 위해서는 EP와 EN의 파형을 동기화시켜놓는 것이 유리하다. 때문에 양극과 음극에서의 전류 및 주기별 유지시간을 Fig. 2과 같이 고정하여 각 극성에 따른 입열의 차이를 최소화하고자 하였다. 한 주기내 양극과 음극의 펄스 비율에 따라 양극과 음극이 교차하는 주기는 변화하는데, 주기내 EN 파형의 비율(R_{EN} , EN pulsing ratio)을 주요 변수로 설정하여 9 수준을 선정하였으며, 한 주기내 반복회수는 3수준 조건을 채택하였다. 예를 들어, 한 주기내 양극과 음극 파형의 비율이 1:3인 경우와 3:9인 경우 같은 0.75의 파형비를 가지지만, 주기내 파형 반복회수는 1회와 3회로 다르다. Table 1에 실험에서 적용한 용접조건을 보다 자세히 나타내었다.

3. 실험결과 및 고찰

3.1 EN 펄스 비율 변화에 따른 파형 비교

피크 주기 동안 (Fig. 2 (6)) 형성된 용적은 단락 주기 동안 용접토크의 푸시-풀(push-pull) 동작에 의

Table 1 Welding conditions applied in the experiment

Variables	Value
Wire feed rate (m/min)	9 (1 level)
Welding speed (m/min)	0.3, 0.5, 0.7 (3 levels)
EN pulsing ratio (EN pulse/Total pulse)	0, 0.1, 0.25, 0.33, 0.5, 0.67, 0.75, 0.9, 1 (9 levels)
Repetition	1, 3, 5 (3 levels)

해 용융풀로 이행되어, 펄스의 개수는 용적 이행의 개수와 일치한다. 주기 내 EN 펄스 비율 및 반복횟수에 따른 파형을 Fig. 3에 나타내었다. 200 ms 동안 단락은 13-14개 발생되며, 펄스 비율 및 극성변화 횟수 등과 무관하게 유사하였다. 계측 파형으로부터 EN 펄스 비율에 따른 전류/전압 및 에너지의 RMS 값을 Fig. 4와 같이 구하였다. EN 펄스 비율이 0.5 보다 작은 정극성 (Electrode polarity, EP)이 주요하게 작용하는 조건에서는 전류/전압 및 입열이 유사하였다. 반면, EN 펄스 비율이 0.5 이상으로 증가하면 전류값이 저하되면서 전체 입열이 줄어드는 경향이 나타났다. 용접 속도 변화가 전류/전압 및 공급 에너지에 미치는 영향은 확인되지 않았다.

용적이행 및 용융풀의 표면형상은 극성에 따라 변화하였다. Fig. 5 (a)-(c)에 EP 극성에서의 용적이행을, (d)-(f)에 EN 극성에서의 용적이행을 나타내었다. Fig. 5 (b),(c)와 (e),(f)는 각 극성에서의 피크와 단락 구간에서의 모습을 나타내는데 아크가 형성되어 있는 구간이기 때문에 아크의 영향을 가시적으로 확인할 수 있다. EP 극성에서는 아크압력으로 인해 용융풀 표면에 처짐이 발생하였으며, EN 극성에서는 용적이 상대적으로 크게 형성되었다.

3.2 EN 펄스 비율 변화에 따른 용접성 비교

극성에 따른 용적이행 및 용융풀 표면의 변화는 용입 및 용적량에 영향을 미치게 된다. Fig. 6에 EN 펄스 비율의 변화에 따른 비드외관을 나타내었다. 극성 변화 빈도는 EN 펄스 비율이 0.5가 될 때까지 증가하면서 이후 다시 감소한다. 극성이 자주 변화하는 경우에서 비드의 리플은 보다 완만하였다. Fig. 6(a)-(e)의 펄스 반복횟수가 1회인 경우보다, Fig. 6(f)-(i)에 나타난 바와 같이 펄스 반복횟수가 3회 또는 5회인 경우 비드 외관의 리플이 보다 뚜렷이 나타났다. EN 펄스 비율이 증가하면 비드의 높이 및 폭이 증가하는 경향이 나타났으며, 높은 입열로 인해 낮은 용접속도 조건에서 빠른 용접속도 조건보다 비드의 높이 및 폭이 크게 측

Fig. 3 Measured current waveform depending on EN pulsing ratio with (a) one and (b) three times repetition

Fig. 4 Measured (a) welding current, (b) voltage and calculated (c) heat input depending on EN pulsing ratio and welding speed (one repetition condition)

Fig. 5 High-speed camera images captured during the droplet transfer depending on phase. ((a) to (c): EP phase, (d) to (e): EN phase). (a) and (d) represent base current period for each phase, (b) and (e) are peak current, (c) and (f) are images for detach current period

	Repe- tition	EN pulsing ratio	Bead appearance
(a)	×1	0	
(b)		0.25	
(c)		0.5	
(d)		0.75	
(e)		1	
(f)	×3	0.25	
(g)		0.5	
(h)	×5	0.25	
(i)		0.5	

Fig. 6 Bead appearances under the variable EN pulsing ratio and repetition. The specimen was fabricated with a welding speed of 0.7 m/min

정되었다 (Fig. 7). 반복 횟수의 증가는 리플의 형성을 촉진시키기 때문에 각 조건에서의 높이 및 폭의 편차가 크게 나타났다. 반복 횟수에 무관하게 비드의 평균 높이와 폭은 유사하게 측정되었다.

용적물의 단면을 확인한 결과, 한 주기내 EN 펄스의 비율이 증가하면 적층면적 또한 증가하는 경향이 나타났다(Fig. 8(a)). 역극성에서 아크가 와이어 상단부에 형성됨에 따라 용가재의 용융이 가속화되었기 때문으로 판단된다. 반면, 부재로의 용입은 EN 펄스 비율이 증가함에 따라 감소하는 경향을 나타내며, 특히 비율이 0.5를 넘어가며 급격히 감소하였다. EN 펄스 비율이 증가함에 따라 모재로의 에너지 전달이 제한되었을 뿐만 아니라, 단락이행 공정의 특성으로 인해 용적의 이행 중 중력의 영향력은 감소하였기 때문으로 판단된다.

Fig. 7 Bead height and width of deposit materials depending on EN pulsing ratio and welding speed under variable repetition conditions of (a) one and (b) five times

Fig. 8 (a) Deposition and dilution area derived from sectional image of the welds, and (b) weight of welds per length of 120 mm depending on EN pulsing ratio and repetition.

용적물의 무게는 EN 펄스 비율과 비례적으로 증가하는 경향을 나타내었으며, 반복횟수가 증가하는 경우보다 선형적으로 증가하였다(Fig. 8(b)). 동일 길이를 용접하였을 때, 극성이 빈번하게 변화하는 EN 펄스 비율 조건(0.5)에서 용착 금속이 추세보다 많이 적층되는 것을 확인할 수 있었다. 이러한 현상은 사용한 극성이 변화하는 과정에서 용접전원이 아크를 안정시키기 위해 전류 공급시간을 제어하기 때문에 나타난 일시적 현상으로 판단된다.

3.3 EN 펄스 비율 변화가 조직형성에 미치는 영향

용접부 조직은 조성, 불순물, 용접조건 등 다양한 요인에 의해 변화할 수 있다. EN 펄스 비율의 변화는 부재의 회석량에 영향을 미치며, 극성 변화에 따른 용융 풀 내부 유동으로 인해 핵생성 기지가 다르게 작용할 수 있다^{14,15)}. 본 연구에서는 냉각속도에 보다 유의하

Fig. 9 (a) Measured temperature and (b) calculated cooling rate depending on EN pulsing ratio. Welding speed and repetition were fixed at 0.5 m/min and three times, respectively

여 논의하고자 하였다. 냉각속도는 온도구배와 응고속도의 상관관계로 설명할 수 있는데, 냉각속도가 빠른 경우 보다 미세한 조직의 형성이 가능하다¹⁶⁾.

아크 중심부 직하 11 mm 깊이에 써모커플을 부착하여 공정 중 온도측정을 실시하였다. Fig. 9에 나타난 바와 같이 최대온도 및 냉각속도는 극성변화 빈도가 가장 높은 EN 펄스 비율이 0.5인 경우에서 측정이 되었으며, 역극성 또는 정극성을 단독으로 활용하는 경우에서 가장 낮게 측정되었다. 같은 변화빈도를 가지고 있어도 주기를 구성하는 극성의 비율에 따라 측정된 온도가 차이가 발생하였다. 이는 Fig. 4의 측정된 파형으로부터 도출된 공급에너지와도 경향이 다르다. 공급 에너지를 사용하는 방식 및 효율이 극성에 따라 차이가 있음을 재확인할 수 있다.

Fig. 10 Microstructure in longitudinal direction depending on EN pulsing ratio and repetition

EN 펄스 비율에 따른 구성조직의 변화를 관찰하여 Fig. 10과 같이 나타내었다. Babu¹⁷⁾은 펄스 용접 중 극성의 변화가 용융풀 내부 유동에 영향을 미쳐특정 결정립 성장을 방해하여 결정립 성장 억제에 원인으로 작용할 수 있다고 언급하였다. 해당 연구에서도 냉각속도가 빨라지는 EN 펄스 비율 0 - 0.5 사이 구간에서는 EN 펄스 비율이 증가함에 따라 주상정 조직보다 등축정 조직이 주도적으로 확인되었다. 극성 변화비율이 낮은 0 - 0.25 조건에서는 열원방향으로 이방성의 상징인 에피텍셜 성장의 흔적이 확인되기도 하였다.

반면, 역극성만 단독으로 활용한 경우에는 공급에너지가 적을 뿐만 아니라, 해당 에너지가 와이어를 용융하는데 상당량 활용되면서 용적의 온도가 정극성 구간에 비해 낮아서 결정립이 작게 형성된 것으로 예측된다. 해당 부분에 대해서는 추가적 고찰 및 분석이 요구되어진다.

4. 결 론

본 연구에서는 가변극성 단락이행 용접전원을 이용하여 한 주기를 구성하는 EN 펄스의 비율 및 반복횟수가 비드형성 및 미세조직에 미치는 영향을 고찰하였으며, 다음과 같은 결론을 도출하였다.

1) EN 펄스 비율 변화는 아크 집중 위치에 직접적 영향을 미쳐 용착량 및 부재의 용융량이 변화를 야기한다. EP 극성이 주도적인 조건에서는 용적의 크기가 작고, 강한 아크 발생으로 인해 용융풀 표면의 처짐이 형성되었다. EN 극성이 주도적인 조건에서는 낮은 입력에너지가 공급되었음에도 용적의 크기가 크고, 아크가 EP 조건에 비해 상대적으로 높은 위치에서 형성되었다. EN 펄스 비율이 증가할수록 적층물의 무게가 증가하는 경향이 나타났으며, 폭과 너비 모두 증가하는 경

향이 나타났다. 주기내 반복횟수가 커질수록 리플이 뚜렷이 관찰되는 형상적 변화는 확인되었으나, 용적물의 무게에 미치는 영향은 미미하였다.

2) 주요 극성 및 극성변화의 빈도수가 결정립 형성에 미치는 영향을 확인하였다. EP 극성에 비해 EN 극성에서 조밀한 크기의 조직의 형성이 가능한 것으로 판단된다. EN 펄스 비율이 높은 조건에서 상대적으로 낮은 입열이 공급되었을 뿐만 아니라, 용적의 용융에 소모된에너지가 많아 용적의 온도가 낮기 때문이다. EN 펄스 비율이 낮은 조건에서는 부여 입열의 중첩으로 인해 일부 조건에서는 에피텍셜 성장이 확인되었다. 이를 통해 Fang¹¹⁾ 및 Cong¹²⁾의 연구결과와 같이 극성변화를 통해 이방성을 억제가 가능함을 재확인하였다. 극성변화의 빈도가 잦아질수록 결정립의 크기는 작아지며, 주기 내 반복횟수가 증가하는 경우 극성변화 빈도수는 줄어들기 때문에 결정립의 크기를 줄이기 위해서는 반복횟수는 적은 것이 유리한 것으로 판단된다.

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