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Flux column effects on metal transfer mechanism in a rutile-type FCAW: insights from comparisons with MCAW and GMAW

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Abstract

This study investigates the role of the flux column in the metal transfer process of Flux-Cored Arc Welding (FCAW). Three rutile-type wires with varying flux ratios were compared with metal-cored and solid wires under Ar-CO₂ shielding at 220–280 A. Transfer frequencies increased with current for all wires. At 280 A, FCAW and Metal-Cored Arc Welding (MCAW) showed higher frequencies (142.9 and 240.5 Hz) than Gas Metal Arc Welding (GMAW) (69.8 Hz). At 220 A, FCAW and MCAW showed similar frequencies (82.1 and 71.8 Hz) attributed to long flux or metal columns (un-melted metal core), which prevented neck formation by the Lorentz force. In the 250–280 A range, the MCAW frequency increased significantly, reaching 168% of FCAW, likely because melting shortened the metal column, allowing the Lorentz force to act more effectively on droplets. Increasing the flux ratio from 12 to 20% slightly reduced flux column length and increased frequency from 131.4 to 162.8 Hz at 280 A. The ratio of Wire Feed Speed (WFS) to transfer frequency was proportional to droplet diameter. WFS increased linearly with current for all wires. Droplet diameters decreased sharply for MCAW (1.60 to 1.20 mm) and GMAW (2.43 to 1.72 mm), but only slightly for FCAW (1.60 to 1.45 mm) in the 220–280 A range. Through comparisons of frequencies and WFSs, the former was a dominant factor for controlling droplet diameters. Consequently, the results suggest that the flux column length governs the droplet size in FCAW.

Keywords Flux-cored arc welding · Flux ratio · Metal transfer · Flux column · Metal column · Iron content

1 Introduction

In the welding industry, productivity gains and cost reduction have been the primary driving forces for fabricators [1]. In arc welding using a wire electrode, molten metal formed at the wire tip, called a droplet, is transferred to a base metal to achieve welding. The deposition rate is one of the most important indicators of performance [1, 2]. This rate is influenced by the welding current and voltage. In traditional Shielded Metal Arc Welding (SMAW), these parameters are constrained by machine settings and, more critically, the welder's skill [2]. To overcome such limitations, Gas Metal Arc Welding (GMAW) was developed, offering higher deposition rates and faster welding speeds than SMAW [2]. However, GMAW generally requires clean workpieces and well-controlled shielding gas conditions. To address these challenges, Flux-Cored Arc Welding (FCAW) was introduced, using a tubular wire with an internal flux surrounded by a metal sheath [1, 3]. While FCAW achieves

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high deposition rates and welding speeds, its wire design and complex flux chemistry make stable metal transfer more difficult to achieve [3].

In GMAW, through both theoretical and experimental works, the mechanism of metal transfer has been clarified extensively [4, 5]. Particular attention has been paid to the current range where the metal transfer mode shifts from globular to spray under different welding conditions [6]. Spray transfer offers clear advantages. Small droplets play important roles in stabilizing the arc, reducing spatter formation, and improving weld bead appearance compared with globular transfer [7, 8]. Furthermore, the droplet diameter has an influence on the surface temperature of droplet, which affects metal evaporation from molten droplet [9]. A smaller droplet causes much less metal evaporation than that from a larger droplet [9–11], decreasing the fume formation rate. To help assess these very important effects of droplet diameter in arc welding, Lowke [12] proposed a force-balance model to discuss the transition from globular to spray modes. In this model, the surface tension is assumed to be balanced against the combined gravitational and Lorentz forces in the droplet, ignoring arc pressure acting on the droplet bottom. The model can estimate droplet diameters in Ar GMAW. Experimental data confirmed its validity for different wire materials [4, 5, 13]. However, this model cannot be applied to cases using Ar-CO₂ mixtures. This is because the arc is strongly constricted under the droplet bottom in GMAW using high CO₂ contents in the mixture, so the arc pressure cannot be ignored [14–19]. For this reason, many further studies have had a particular focus on clarifying the driving forces governing the metal transfer process in Ar-CO₂ mixtures [16–18].

Ogino et al. [16] reported that the transition current increased from 230 A for pure argon gas to 280 A for 18% CO₂ in Ar-CO₂ mixtures. This increase resulted from changes in the driving forces acting on the droplet. In the Ar-CO₂ mixture, the current was concentrated at the droplet bottom due to the arc constriction caused by an increase in the specific heat of the mixture, strengthening the arc pressure. As a result, the droplet detachment was hindered, leading to the formation of large droplets. This indicates that the metal transfer behavior strongly depends on the distribution of the current paths. The spray transfer mode occurs more easily when the current path expands toward the wire tip [17]. The current path itself is determined primarily by the electrical conductivity distribution of the arc plasma and by the morphology of the droplet [19]. In addition to the constricted arc under CO₂ gas, a sufficient amount of metal vapor evaporated from the droplet might also alter the situation. The dense metal vapor plasma emits intense radiation, substantially decreasing the plasma temperature, lowering the electrical conductivity near the arc axis. Therefore, the current path no longer concentrates beneath the droplet [17].

Thus, regulating the electrical conductivity of metal vapor provides a means to control the transfer mode.

Besides, the composition of the arc plasma is significantly different depending on the droplet morphology [18]. In CO₂ arc welding using a steel electrode, iron vapor filled the entire plasma when droplets were symmetrical. In contrast, with asymmetrical droplets, the high-temperature region and the dense iron vapor region were separated. As a result, the arc pressure increased, the droplet was pushed upward, and the transfer shifted to a repelled mode, resulting in extensive spatter. Building on this understanding, Sato et al. [20] showed that wires with higher electrical conductivity reduce the internal gradient of electromagnetic pressure in the droplet. At the same time, the arc pressure beneath the droplet increases. Both effects raise the transition current required for spray transfer. Further, an advanced control method using a vibrating electrode was proposed [21]. In this case, the inertial force from droplet oscillation assists detachment. Transfer occurs at a higher frequency than in conventional GMAW. These studies highlight the importance of clarifying the mechanisms of metal transfer in GMAW. However, this kind of research in FCAW is significantly limited, underscoring the need for further systematic investigations.

Most relevant studies focused on underwater FCAW [22–26]. In contrast, investigations of FCAW conducted in air remain very limited. The mechanism of the metal transfer process in FCAW is known to be significantly different from that in GMAW using a solid wire introduced above, because of differences in the wire structure. A large part of the current in the flux-cored wire is believed to be conducted through the metal sheath, avoiding the internal flux with a low electrical conductivity, affecting the Lorentz force acting on the droplet. The presence of a flux column (the unmelted core components in tubular wires) might prevent neck formation. The composition of the vapor is also predicted to change depending on the flux composition. Some of the earliest works on metal transfer in FCAW were conducted by Matsuda et al., although the flux composition was not provided in their papers [27–30]. They found that sodium added to the flux promoted smoother and more regular transfer [29], increasing the transfer frequency and reducing the droplet diameter. Building on this, Le et al. [31] investigated the influence of sodium in rutile-type FCAW, whose main flux component is TiO₂. They showed that an optimal sodium content allowed part of the current to flow through the sodium plasma beside the flux column, thus reducing the arc pressure under the bottom of the droplet and prompting droplet detachment. In contrast, at high sodium content, sodium plasma concentrated in the arc center. The resulting recoil pressure, due to excessive sodium evaporation, hindered detachment. Besides, a change in wire structure from hollow (a completely hollow core) to fold-shaped (the folded wire sheath separates the core) alters the detachment

mechanism [27]. In the hollow design, droplets detach explosively at the wire tip. In the folded design, droplets detach together with the falling flux column. The role of the flux column was discussed to explain the metal transfer behavior in both FCAW and Metal-Cored Arc Welding (MCAW) [14, 15, 28, 32]. It was found that the droplet had to flow downward along the column and reach its tip before detachment in FCAW [15]. Ngoc et al. [14] and Tashiro et al. [32] reported that the neck formation could start when the arc attachment on the wire was formed at a lower height than the end of the flux column in MCAW, because it was a necessary condition for the Lorentz force to act on the droplet effectively. Thus, the length of the flux column played an important role in the metal transfer frequency. As mentioned above, it is a fact that the flux column was always formed in FCAW and MCAW [14, 15, 28, 31–34]. However, its length may vary significantly with flux composition. The variation arises from differences in the physical properties of fluxes, which consist of iron in MCAW and TiO_2 in rutile-type FCAW, with other minor components. This raises the question of how changes in the flux column affect the metal transfer mechanism. Despite the widespread use of FCAW, the role of the flux column in stabilizing or destabilizing metal transfer remains insufficiently understood.

In this study, the role of the flux column in the metal transfer mechanism in rutile-type FCAW was clarified. Three flux-cored wires with different flux ratios were used to compare the metal transfer characteristics (metal transfer frequency and droplet diameter) with those of commercial metal core and solid wires. In particular, the mechanism by which the formation of small droplets becomes a critical factor for stabilizing the arc was discussed. The experiments were conducted at three welding currents using a mixture of Ar-20% CO_2 shielding gas. The shadowgraph method was used to capture the metal transfer behavior and arc appearance during welding. The influence of the flux column was analyzed based on the recorded high-speed videos.

2 Experimental methodology

2.1 Welding conditions and materials

Bead-on-plate welding experiments using mild steel plates (SS400 – JIS 3101) were conducted for the FCAW, MCAW and GMAW processes. Three types of experimental rutile flux-cored wires, classified as AWS A5.20 E71T-1C with a diameter of 1.2 mm, were primarily used. These wires contain flux mass ratios of 12%, 16%, and 20%, and are referred to throughout this paper as F12, F16 (standard wire), and F20, respectively. For comparison, a commercial 1.2-mm-diameter metal-cored wire with a powder core ratio of 15% (M) and solid (S) wire with the classification

of AWS A5.20 E70T-1C and JIS Z3312 YGW11, A5.18 ER70S-G, respectively, were also included to evaluate differences in metal transfer behavior relative to the flux-cored wires. The chemical compositions of the fluxes used in the experimental wires are listed in Table 1. It is presented that the iron content largely increased with increasing the flux ratio to keep the contents of other components. Additionally, cross-sectional observations of the flux-cored wires were performed, as shown in Fig. 1.

The experiments were performed using a welding power source (DP-350, OTC Daihen) with a wire feeder, operating in Direct Current Electrode Positive (DCEP) mode, and with Constant Voltage (CV). A constant Contact Tip to Workpiece Distance (CTWD) of 20 mm was maintained throughout all trials. Moreover, the wire extension was consistently maintained at 10 mm prior to each experiment. The base metal was positioned on a moving table to ensure a consistent welding speed of 5 mm s^{-1} . To clarify the influence of the flux column on the metal transfer mechanism in FCAW compared with this in MCAW and GMAW, the experiments were conducted at three current levels: 220 A (low current), 250 A (medium current), and 280 A (high current). The welding voltage ranged from 29 to 33 V to maintain a stable arc length. A shielding gas mixture of argon with 20% CO_2 at a flow rate of 20 L min^{-1} was used. The summary of welding conditions is presented in Table 2. In addition, the Wire Feed Speed (WFS) as a function of current was obtained from the welding machine panel before carrying out the weld. Figure 2 shows the wire feed speed as a function of welding current for the different wires for GMAW (S), MCAW (M) and FCAW (F12, F16 and F20).

2.2 Metal transfer and arc appearance observation

Figure 3 illustrates the schematic of the experimental setup used to observe the metal transfer behavior and arc appearance. A shadowgraph method was applied using a High-Speed Video Camera (HSVC) (Memrecam Q1v, Nac Image Technology) equipped with a Micro-NIKKOR objective lens (Nikon) featuring a 200 mm focal length and a 1:4 focus ratio. A 640-nm wavelength laser illumination system (Cavilux HF, Cavitar) was employed as a backlight source for the shadowgraph method. In this study, the camera, wire tip, and laser lens were aligned along a single axis. The line

Table 1 Chemical compositions of the fluxes used in the experimental wires (mass%)

Wire	Fe	TiO_2	Mn	Si	Al
F12	14.9	45.2	19.1	5.3	0.8
F16	35.1	33.9	14.3	4.1	0.6
F20	47.2	27.1	11.5	3.3	0.5

Fig. 1 The cross-sectional observation of flux-cored wires: (a) F12, (b) F16 and (c) F20

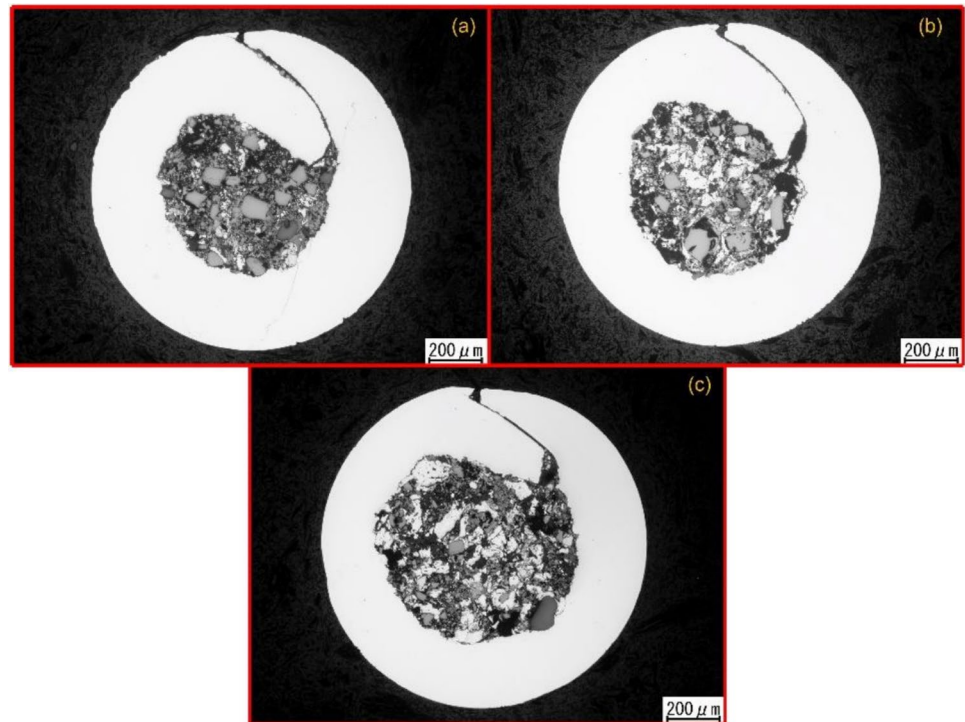
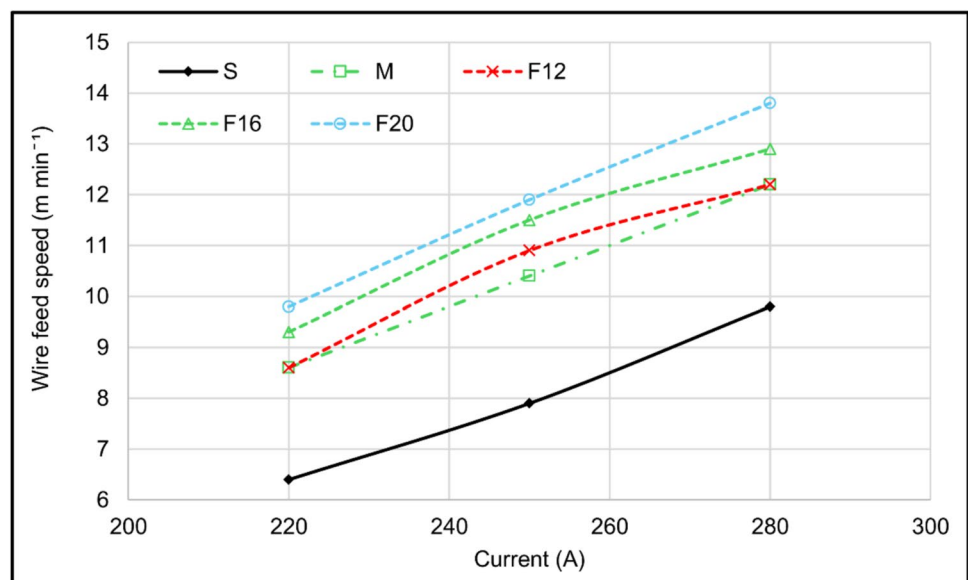


Table 2 Welding Conditions

Welding parameters	Value
Welding current levels	220 A, 250 A and 280 A
Arc voltage	29 V—33 V
Welding velocity	5 mm s ⁻¹
CTWD	20 mm
Shielding gas	Ar-20% CO ₂ ; 20 L min ⁻¹

connecting the centers of the objective lens and the laser lens was perpendicular to both the wire axis and the welding direction. The distances from the front surface of the laser lens to the wire tip and from the front surface of the objective lens to the wire tip were set to 300 mm and 600 mm, respectively. The camera was operated at 4000 frames per second, with an aperture of f/5.6 and an exposure time of 26 μ s. To minimize arc brightness caused by radiation, six

Fig. 2 Wire feed speed as a function of welding current for the different wires for GMAW (S), MCAW (M) and FCAW (F12, F16 and F20)



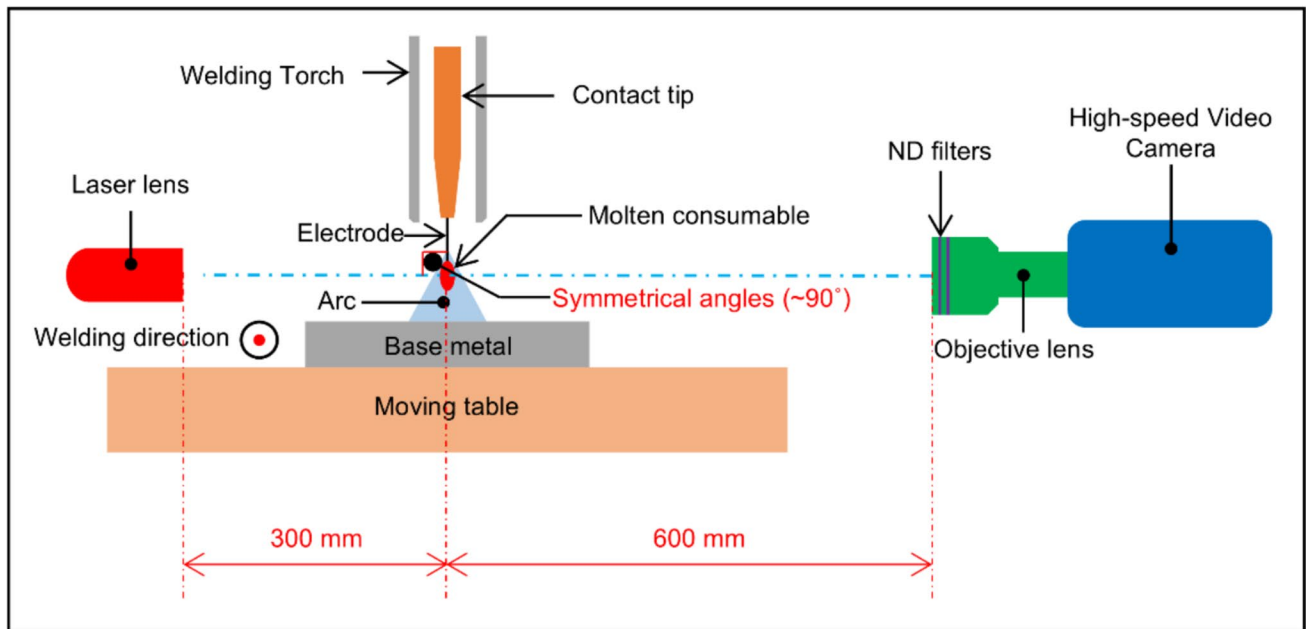


Fig. 3 Schematic of experimental setup for observing the metal transfer behavior and arc appearance using shadowgraph method

neutral density (ND) filters, five ND-8 and one ND-4, were used. Although a bandpass filter matching the illumination wavelength is typically employed to further suppress arc radiation in shadowgraph method, only ND filters were used in this study to allow simultaneous observation of both metal transfer behavior and arc appearance during the experiments.

3 Results

3.1 Metal transfer frequency

Figure 4 shows (a) the metal transfer frequency and (b) equivalent droplet diameter as a function of welding current for the different wires in GMAW (S), MCAW (M) and FCAW (F12, F16 and F20). The overall frequency was determined by averaging ten independent calculations. Each calculation was obtained from counting droplets within randomly chosen 250-ms durations of a 4-s video. The error bars indicated the standard deviation.

In FCAW, the transfer frequencies were $75.0 \text{ Hz} \pm 7.5 \text{ Hz}$, $82.1 \text{ Hz} \pm 3.0 \text{ Hz}$, and $93.2 \text{ Hz} \pm 6.0 \text{ Hz}$ at 220 A for the wires with flux ratios of 12%, 16%, and 20%, respectively. When the current rose to 250 A, the frequencies also rose to $93.2 \text{ Hz} \pm 5.2 \text{ Hz}$, $101.3 \text{ Hz} \pm 4.0 \text{ Hz}$, and $113.6 \text{ Hz} \pm 5.0 \text{ Hz}$ with the same increasing flux ratios. At 280 A, droplet detachment was even faster, pushing the frequencies to $131.4 \text{ Hz} \pm 9.9 \text{ Hz}$, $142.9 \text{ Hz} \pm 12.6 \text{ Hz}$, and $162.8 \text{ Hz} \pm 13.0 \text{ Hz}$. It could be inferred that the metal transfer frequency generally increased as the flux ratio became higher,

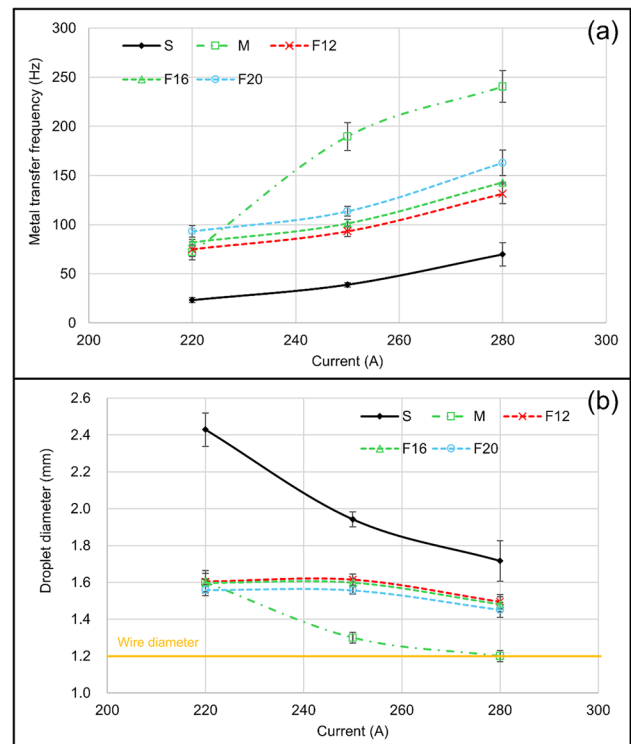


Fig. 4 (a) Metal transfer frequency and (b) equivalent droplet diameter as a function of welding current for the different wires in GMAW (S), MCAW (M) and FCAW (F12, F16 and F20)

regardless of the welding current. However, the rise in frequency in FCAW with either currents or flux ratios was not extremely large.

In MCAW, the metal transfer frequency increased significantly with increasing current. However, at a low current of 220 A, the metal transfer frequency was $71.8 \text{ Hz} \pm 7.6 \text{ Hz}$, which was almost the same as those in FCAW. When the current increased, the frequencies rose to $189.7 \text{ Hz} \pm 14.1 \text{ Hz}$ and $240.5 \text{ Hz} \pm 16.2 \text{ Hz}$ at 250 A and 280 A, respectively. These values were significantly higher than those in FCAW at the same currents. The increase in frequency with current in MCAW was remarkable compared to the solid wire case. In GMAW, the frequency increased gradually from $23.1 \text{ Hz} \pm 2.4 \text{ Hz}$ at 220 A to $69.8 \text{ Hz} \pm 11.8 \text{ Hz}$ at 280 A.

Overall, the results showed that both FCAW and especially MCAW produced much higher metal transfer frequencies than GMAW as current increased. However, the frequency deviation due to flux core ratios in FCAW was less predictable.

Figure 4b shows the equivalent droplet diameters for the flux-cored wires compared to metal-cored and solid wires. In this study, the wire melting rate was considered as the product of the WFS (v_{wfs}) and wire cross-sectional area (S_w), while the droplets were assumed to be spherical [35]. From the calculated transfer frequencies, the droplet volume was then estimated as follows:

$$V = \frac{v_{\text{wfs}} S_w}{f} \quad (1)$$

where V represents the droplet volume and f depicts the metal transfer frequency.

From this volume, the equivalent droplet diameter can be expressed as the following equation:

$$d = \sqrt[3]{\frac{6 \times V}{\pi}} \quad (2)$$

where the equivalent droplet diameter is represented by d . The error bars represent the standard deviation of these calculations.

The results indicate that in FCAW, the droplet diameters decreased slightly from $1.60 \text{ mm} \pm 0.06 \text{ mm}$ to $1.50 \text{ mm} \pm 0.04 \text{ mm}$ for F12, from $1.60 \text{ mm} \pm 0.02 \text{ mm}$ to $1.48 \text{ mm} \pm 0.04 \text{ mm}$ for F14, and from $1.56 \text{ mm} \pm 0.03 \text{ mm}$ to $1.45 \text{ mm} \pm 0.04 \text{ mm}$ for F20 when current increased from 220 to 280 A, respectively.

In contrast, the droplet diameters in GMAW and in MCAW decreased steeply as the current increase. For metal-cored wire, the droplet diameter varied from $1.60 \text{ mm} \pm 0.05 \text{ mm}$ at 220 A to approximately $1.20 \text{ mm} \pm 0.03 \text{ mm}$ at 280 A. Notably in GMAW, the droplet diameter reduced dramatically from $2.43 \text{ mm} \pm 0.09 \text{ mm}$ at 220 A to $1.72 \text{ mm} \pm 0.11 \text{ mm}$ at 280 A.

The results suggested that the metal transfer mode was mostly globular for all wires at all current levels. This mode is characterized by droplet diameters larger than the wire diameter [3, 6, 33, 36, 37]. Even for the metal-cored wire at 280 A, the droplet diameter was very close to the wire diameter of 1.20 mm, defined as spray transfer [3, 6, 33, 36, 37].

For further insight, the next section will present an analysis of the high-speed videos taken during the experiments.

3.2 Metal transfer behavior and arc appearance

To better understand metal transfer behavior, this section presents synchronized high-speed images of the metal transfer behavior and arc appearance. Those were captured using the shadowgraph technique. The analysis included comparisons of metal transfer behavior and arc appearance for three flux-cored wires at medium current, the standard flux-cored wire at three different current levels, and typical images of flux-cored, metal-cored, and solid wires at medium current.

Firstly, Fig. 5 shows time-sequential images during one cycle of metal transfer for (a) F12, (b) F16, and (c) F20 wires at 250 A in FCAW with Ar-20% CO₂ shielding gas. One cycle is measured from one detachment to the next. The detachment times were mostly similar: 10.50 ms for F12, 10.00 ms for F16, and 8.75 ms for F20.

In all cases, the molten droplet was larger than the wire diameter before detachment. This agreed with the calculated droplet diameters in Sect. 3.1. The droplet was offset from the wire's center, then grew and flowed downward along the flux column [15].

The figure also shows that the gas plasma attachment was located at the higher part of droplet for all flux-cored wires during welding in FCAW. At the moment of droplet detachment, the metal plasma was closely aligned with the gas plasma attachment. After that, this plasma gradually shifted to a position under the droplet just before detachment at 8.00 ms for F12, 6.00 ms for F16, and 5.25 ms for F20.

Next, the effects of welding current on metal transfer behavior and arc appearance for the standard flux-cored wire (F16) are shown. Figure 6 presents time-sequential images during one cycle of metal transfer for F16 at (a) 220 A, (b) 250 A, and (c) 280 A in FCAW with Ar-20% CO₂ shielding gas.

The images show that as the current increased from 220 to 280 A, the droplet formation position shifted from the side of wire to the center. This agreed with the findings reported by Le et al. [31]. Higher current also produced smaller and more symmetrical droplets. When the current increased from 220 to 280 A, the duration for detachment decreased from 13.25 ms down to 8.50 ms, respectively.

At low current, the flux column was maintained during droplet growth and broke immediately after detachment. At high current, it broke earlier and fell into the weld

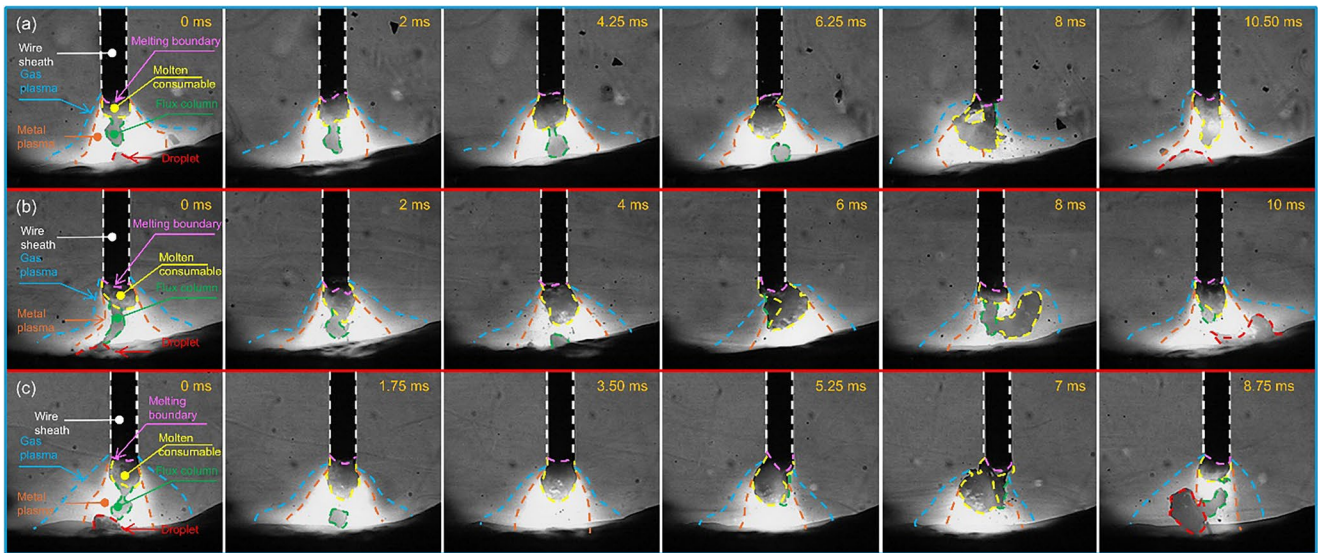


Fig. 5 Time-sequential images during one cycle of metal transfer for (a) F12, (b) F16 and (c) F20 wires at 250 A in FCAW using Ar-20% CO₂ shielding gas

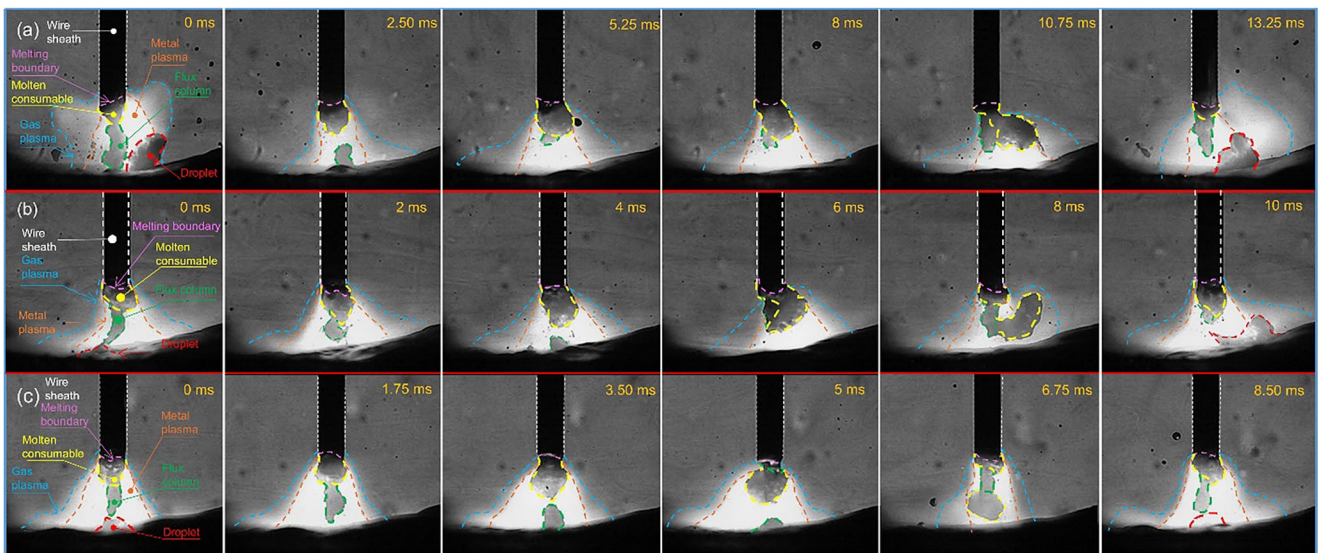


Fig. 6 Time-sequential images during one cycle of metal transfer for F16 wire at (a) 220 A, (b) 250 A and (c) 280 A in FCAW using Ar-20% CO₂ shielding gas

pool during droplet growth (seen at 3.50 ms in Fig. 6c). At medium current, a mix of both behaviors of the flux column was observed. Overall, the flux column became shorter as the current increased.

The figure also illustrates how the arc appearance changed. At 220 A, the arc behavior was similar to that in all flux-cored ratio wires at 250 A, as shown in Fig. 5. The gas plasma attachment remained at the higher part of droplet, while the metal plasma moved from the higher part of droplet to under the droplet just before detachment. At 280 A, however, the metal plasma remained near the wire tip and

aligned with the gas plasma attachment, covering the molten droplet throughout its growth.

Finally, Fig. 7 shows the typical images of metal transfer behavior and arc appearance at 250 A for GMAW, MCAW and FCAW using Ar-CO₂ shielding gas. The wires were (a) S, (b) M, (c) F12, (d) F16 and (e) F20.

In GMAW, a large molten droplet formed with a neck near the wire tip. In contrast, MCAW produced a small molten droplet with a narrow neck that remained centered on the wire. Its diameter ($1.30 \text{ mm} \pm 0.03 \text{ mm}$) was nearly equal to that of the wire itself. In addition, the droplet fully

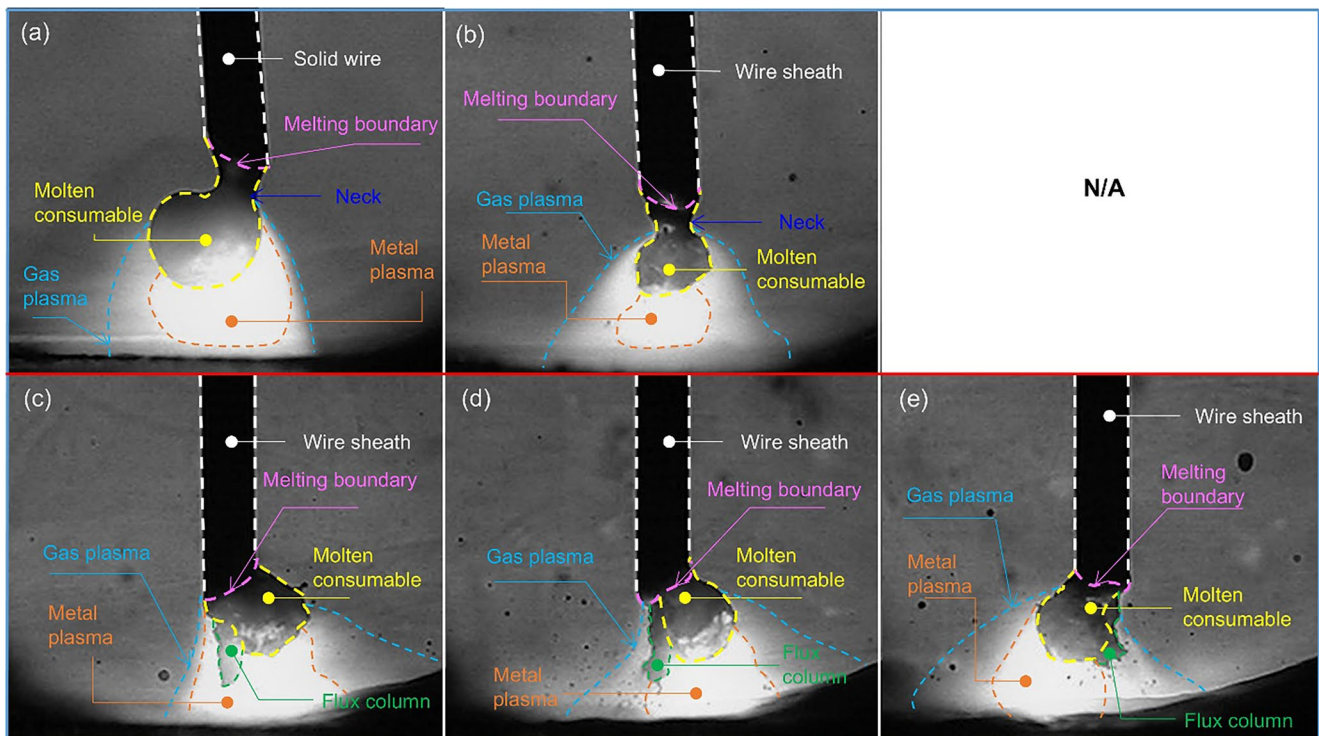


Fig. 7 Typical images of metal transfer behavior and arc appearance at 250 A in GMAW, MCAW and FCAW using Ar-CO₂ shielding gas. (a) S, (b) M, (c) F12, (d) F16 and (e) F20

enveloped the flux column. In FCAW, however, the droplet consistently appeared offset from wire center, leaving part of the flux column exposed. As the flux ratio increased, the exposed flux column in FCAW became slightly shorter.

The arc appearance varied noticeably among the three welding processes at 250 A. Overall, the arc in GMAW was more constricted compared to that in MCAW and FCAW. In all cases, metal plasma formed under the droplet as it grew. In GMAW, the gas and metal plasmas were closely overlapping. The arc plasma concentrated on the lower half of the droplet, as shown in Fig. 7a. In contrast, as depicted in Fig. 7b, MCAW showed a clearer separation between the gas plasma and metal plasma: the gas plasma attached near the wire tip, while the metal plasma appeared as a small region under the bottom of the droplet. Figure 7c-e show a hybrid arc appearance in FCAW, combining features from both GMAW and MCAW: the gas plasma was attached at higher part of droplet as in MCAW, while a constricted metal plasma was present under the droplet, resembling the GMAW case.

The findings show the different characteristics of metal transfer and arc appearance between flux-cored, metal-cored and solid wires. Their effects on metal transfer frequency and droplet diameter are discussed in the next section.

4 Discussion

This section discusses the metal transfer mechanism in FCAW based on experimental findings. The focus is on the metal transfer characteristics in rutile-type FCAW, compared with MCAW and GMAW, presented in the previous section. As presented in Eqs. 1 and 2, the droplet diameter is proportional to the WFS divided by metal transfer frequency. It is considered that the former primarily depends on energy balances, and the latter on force balances.

Figure 8 summarizes the factors affecting metal transfer behavior in FCAW with the three flux-cored wires compared to MCAW and GMAW using Ar-CO₂ shielding gas at 250 A. This figure features the schematics for the wires of (a) S, (b) M, (c) F12, (d) F16 and (e) F20.

Metal transfer characteristics were evaluated for flux-cored wires with different flux ratios, a commercial metal-cored wire in MCAW, and a solid wire in GMAW. These wires have the same diameter of 1.2 mm. The experiments were conducted at three welding currents using an Ar-20%CO₂ shielding gas mixture. The results showed that the metal transfer frequency in MCAW was in good agreement with the values of $67.8 \text{ Hz} \pm 14.5 \text{ Hz}$ at 220 A,

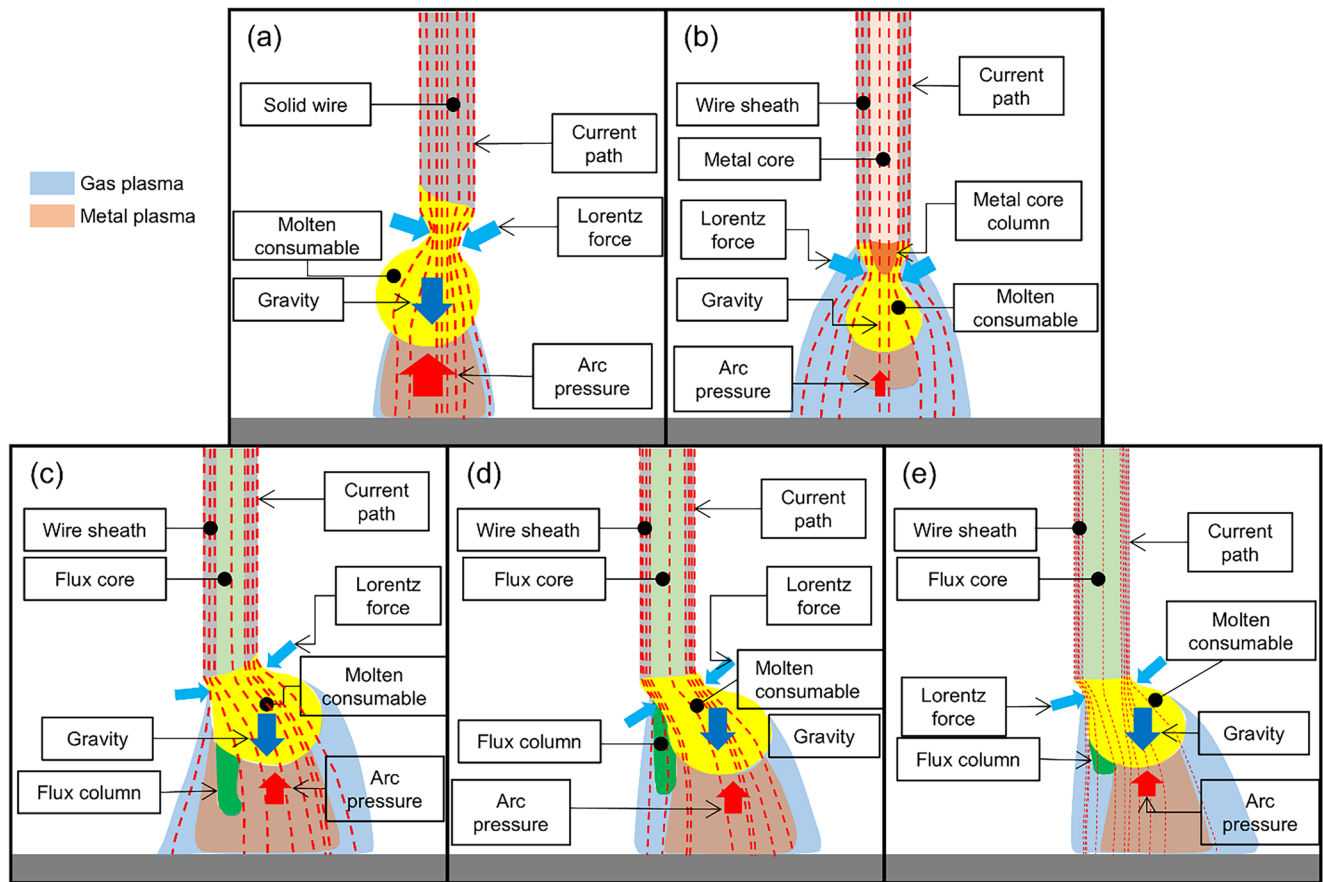


Fig. 8 Schematics of factors affecting metal transfer behavior in FCAW with three flux-cored wires compared to MCAW and GMAW using Ar- CO_2 shielding gas at 250 A, where each schematic shows the wires of (a) S, (b) M, (c) F12, (d) F16 and (e) F20

143.2 Hz $\pm$ 25.0 Hz at 250 A, and 258.8 Hz $\pm$ 10.8 Hz at 280 A reported by Trinh et al. [14].

First, the energy balance is discussed. In this study, the power source was operated with Constant Voltage (CV) characteristics. This setting kept arc voltage constant to maintain a stable arc length under a fixed WFS [2]. Besides, the electrical conductivity for both the metal core and flux core is very low [6, 14, 15, 23, 34]. As a result, most of current is conducted through the wire sheath for the metal-cored and flux-cored wires, thus concentrating the heat input in this region. The WFSs for metal-cored and flux-cored wires are thought to primarily depend on the melting rate of sheath, because it is only necessary for the sheath to melt to maintain a constant arc voltage. The variation in WFSs between solid wire and core wires can be explained by the difference in current conduction areas. Under the same heat input to the wire, the solid wire required heating of the full cross-sectional area of 1.2 mm in diameter, while the core wires required heating of only the sheath area of the wire with the same diameter. Therefore, the core wires melt faster than the solid wire.

The unmelted part of the metal core (referred to as the “metal column” in the remaining parts of this paper) and flux column remained when the sheath melted faster than the core due to the core’s lower electrical conductivity [28, 31]. The variation in electrical conductivity between both cores might lead to the difference in WFSs between the metal-cored and flux-cored wires. Here, the WFSs were compared for a metal-cored wire with a 15% iron powder mass ratio and a flux-cored wire with a 16% flux mass ratio. Even though both cores have very low electrical conductivity, the iron powders have higher conductivity than the TiO_2 powders. Consequently, a larger part of the current conducting in the wire is thought to be shunted through the core in the metal-cored wire than the flux-cored one. Matsuda et al. [25] showed that increasing the iron content inside the core from 0 to 100% reduced the electric resistivity of the wire from 14.0 $\mu\Omega\text{m}$ to 11.9 $\mu\Omega\text{m}$. This reduction lowered the current conducted in the sheath of the metal-cored wire compared with the flux-cored wire, which led to a lower WFS for the metal-cored wire.

In case of flux-cored wires, when the flux ratio inside the core increased, the sheath area decreased to keep the same wire diameter. Although the iron content increased with increasing flux ratio as presented in Table 1, the influence of increase in iron content on WFS was found to be less than that of the decrease in the sheath area. Thus, at the same current, the higher flux ratio resulted in higher WFS.

Next, the force balances governing the metal transfer frequency are discussed. In GMAW, the surface tension, arc pressure, drag force, gravity and Lorentz force are the main factors affecting droplet detachment [4, 5, 8, 19, 21]. Surface tension and arc pressure are upward forces that hinder droplet detachment. Arc pressure, formed by the Lorentz force within the arc, rises when current concentrates beneath the droplet. Downward forces include gravity, which is more significant at low currents, and the drag force from the plasma flow, which is usually negligible. The Lorentz force's direction in the droplet depends on the current path: a conical path drives it downward and inward, while a vertical path pushes inward only. This path depends on the electrical conductivity of the plasma and droplet morphology [19].

As presented in Figs. 7a and 8a, in GMAW, the current path is generally uniform across the wire cross section. The arc attachment was located at the lower part of droplet (Figs. 7a and 8a). This allowed current to pass directly from the bottom of droplet to the weld pool through the arc plasma. The vertical path induced a strong inward Lorentz force, increasing the arc pressure acting on the bottom of droplet [14, 16, 17, 19]. As a result, the droplet detachment was opposed. The Lorentz force acted on the droplet is expected to be smaller than in MCAW and FCAW due to the lower current density in the wire. This explained the lower metal transfer frequency for GMAW compared with MCAW and FCAW.

At a low current, MCAW and FCAW showed almost the same metal transfer frequency. Both the metal and flux column's lengths were longer at a low current than those at high currents. The metal column in MCAW was much shorter than the flux column in FCAW due to its lower melting point. It formed only inside the droplet without penetrating the droplet in most cases, so it is difficult to directly observe it during welding. Ngoc et al. investigated the variation in the metal column lengths at 220 A, 250 A and 280 A by analyzing the wire cross-sections using a Scanning Electron Microscope (SEM) after welding. The results indicated that the tip of metal column reached around the center of droplet at 220 A, but the metal column length shortened with increasing current. At 280 A, the tip of metal column was positioned at the same height as the unmelted metal sheath [34]. As described in the introduction, the length of metal and flux columns is thought to affect the metal transfer frequency [14, 32]. The neck formation could start when the arc attachment occurred at a lower height than the end

of metal column in MCAW. Therefore, the following two points are proposed as reasons why both the frequencies were almost the same: one is that both the metal column and flux column lengths were long enough to prevent the Lorentz force acting on the droplet effectively enough for neck formation (and subsequent detachment) to occur. The second is that the Lorentz force was negligibly small at this current, so the presence of the column did not affect the frequency. Thus, comparable metal transfer frequencies for MCAW and FCAW occurred, as shown in Fig. 4.

When the current increases, the Lorentz force became stronger [12, 19], and the metal column in MCAW becomes shorter and is covered by the droplet as explained above [14, 32, 34]. As shown in Figs. 7b and 8b, according to the short metal column, the Lorentz force acted on the droplet sufficiently for neck formation to occur. Furthermore, the arc attachment was expanded upward to cover almost the entire droplet. The current path took a conical shape, producing a strong downward and inward Lorentz force acting on the droplet. These factors shortened the droplet detachment duration as current increased. As a result, a steep increase in the metal transfer frequency occurred when increasing current in MCAW.

In FCAW, as shown in Figs. 7c-e and 8c-e, a longer flux column was always formed during welding regardless of the current. This hindered the neck formation by the Lorentz force at all the currents, which was decisively different from the MCAW case. The droplet had to be transported downward along the flux column to detach at its end, resulting in a longer detachment duration [15]. Therefore, the slight decrease in the flux column length with current presented in Fig. 6 can lead to a shorter droplet detachment duration. In addition, the droplet was biased from the wire center in FCAW, and the arc attachment covered only the bottom half of droplet, being lower than in MCAW (Figs. 7c-e and 8c-e). This increased the current conducted through the bottom of the droplet in FCAW, which raised the arc pressure on the droplet bottom. Consequently, FCAW showed lower metal transfer frequencies than MCAW at medium and high currents.

When increasing the flux ratio in FCAW, the length of the flux column decreased due to the higher iron content (which has a low melting point compared to TiO_2) in the flux [12, 29]. The droplet is generally transported downward along the flux column before detachment, so the flux column length is considered to affect the droplet detachment duration. Another possible explanation is that the Lorentz force increased with the flux ratio due to the increase in current density in the sheath, enhancing the detachment. As a result, the metal transfer frequency of the flux-cored wire increased slightly at the same current as the flux ratio increased.

Finally, the difference in droplet diameter is discussed. For solid wire, the WFS was low, and the metal transfer

frequency was also very low. This produced very large drop-lets. Although the WFS for MCAW was almost 10% lower than that for FCAW with a standard flux-cored wire, the droplet diameter in MCAW was about 20% smaller than in FCAW at medium and high currents. As in Eq. 2, this can be explained by the significantly higher frequencies in MCAW at medium and high currents compared to FCAW.

The metal transfer frequency in MCAW and FCAW is considered to depend primarily on the column length. These lengths play an important role in determining droplet diameters through changes in droplet detachment process for core wires.

5 Conclusion

This study clarified the roles of the flux column (the unmelted flux core components) in governing the metal transfer characteristics, specifically the metal transfer frequency and droplet diameter in Flux-Cored Arc Welding (FCAW) using different flux ratio wires, compared with those for Metal-Cored Arc Welding (MCAW) and Gas Metal Arc Welding (GMAW) using a solid wire. The main conclusions can be summarized as follows:

1. The metal transfer frequency increased with welding current under all the conditions. GMAW exhibited the lowest frequency, primarily due to the higher arc pressure acting on the bottom of the droplet caused by the lower arc-attachment position.
2. At 220 A, FCAW produced a frequency of 82.1 Hz, comparable to 71.8 Hz in MCAW. However, at higher currents (250 A and 280 A), FCAW frequencies increased to 101.3 Hz and 142.9 Hz, respectively – much lower than the corresponding MCAW frequencies of 189.7 Hz and 240.5 Hz.
3. The relatively high frequencies in MCAW at 250 A and 280 A were considered to be caused by the enhanced neck formation due to reduction in the length of the metal column (the unmelted metal core components) due to melting in MCAW. In FCAW, the longer flux column hindered the neck formation driven by the Lorentz force. The droplet then took longer to fall along the flux column, lowering the transfer frequency. In addition, the arc attachment on the droplet in FCAW was formed at a lower part of droplet than that in MCAW, which is expected to produce a higher arc pressure. This is also considered to lower the metal transfer frequency for FCAW.
4. When the flux ratio increased in FCAW, due to the lower melting point of iron compared to TiO_2 , the higher flux ratio wire with higher iron content in the flux made the flux column slightly shorter. In addition, the Lorentz force would increase due to higher current density in the sheath. The combination of these two factors governed a slight increase in the metal transfer frequency with a higher flux ratio from 131.4 to 162.8 Hz at 280 A.
5. Droplet diameters in MCAW and GMAW decreased sharply with increasing current – from 1.60 to 1.20 mm in MCAW and from 2.43 to 1.72 mm in GMAW as current increased from 220 to 280 A. In contrast, FCAW presented only a slight decrease in droplet diameter from 1.60 to 1.45 mm as the welding current or flux ratio increased due to presence of the long flux column.
6. The droplet diameter is proportional to Wire Feed Speed (WFS) divided by the metal transfer frequency. This variation was found to primarily depend on the metal transfer frequency rather than the WFS.
7. The metal transfer frequency in MCAW and FCAW are considered to primarily depend on the column length. These lengths play an important role in determining droplet diameters through changes in the droplet detachment process for core wires.

This study presented important insights into the metal transfer mechanism for flux-cored wire. If the core wire structure can cause the arc plasma attachment location to be raised toward the wire tip and shorten the flux column as occurs in the metal-cored wire, stable metal transfer with small droplets can be achieved in FCAW. These characteristics enhance welding performance and productivity.

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Data availability Data can be available based on the requirements to verify this work.

Declarations

Competing interests The authors declare no competing interests.

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