Mechanically assisted droplet transfer process in gas metal arc welding

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Abstract: Gas metal arc welding has been generally accepted as the preferred joining technique due to its advantages in high production and automated welding applications. Separate control of arc energy and arc force is an essential way to improve the welding quality and to obtain the projected metal transfer mode. One of the most effective methods for obtaining separate control is to exert an additional force on the metal transfer process. In this paper, the droplet transfer process with additional mechanical force is studied. The welding system is composed of an oscillating wire feeder. The images of molten metal droplets are captured by a high-speed digital camera, and both the macroscopic appearance and the cross-sectional profiles of the weld beads are analysed. It is shown that the droplet transfer process can be significantly improved by wire electrode oscillation, and a projected spray transfer mode can be established at much lower currents. By increasing the oscillation frequency, the droplet transfer rate increases while the droplet size decreases. In addition, the improvement in the droplet transfer process with wire oscillation leads to an enhancement of the surface quality and a modification of the geometry of the weld beads that could be of importance for overlay cladding and rapid prototyping based on deposition by welding.

Keywords: gas metal arc welding, wire oscillation, droplet transfer, rapid prototyping

1 INTRODUCTION

Gas metal arc welding (GMAW) has been generally accepted as the preferred joining technique owing to its advantages in high production and automated welding applications [**1**, **2**]. More recently, the GMAW process has been incorporated into the field of layered deposition manufacturing or rapid prototyping of fully dense metallic parts and is usually termed three-dimensional welding or deposition by welding [**3**–**6**]. However, a better understanding of the metal transfer mechanisms involved in the GMAW process is still imperative and would be most useful for precise control of the geometry and the quality of the weld bead and/or the deposited layers [**6**–**9**], as well as for control of heat input in the substrate.

The metal transfer process in typical GMAW consists of two stages:

1. A droplet forms at the tip of the consumable wire electrode under the effects of arc heating and melting.
2. The droplet detaches from the wire tip and drops into the molten pool produced at the workpiece surface.

The primary retaining force of the droplets is the surface tension of the molten metal, and the primary detaching forces are composed of gravity, shielding gas dragging and electromagnetic pinching. Basically, there are three modes of metal transfer in the GMAW process, i.e. short-circuiting transfer, globular transfer and spray transfer. Among these modes, only the spray mode can produce a very stable spatter-free transfer of small droplets that is necessary for the formation of a uniform accurate bead shape [**1**]. Nevertheless, the spray transfer mode can be obtained only at high current levels exceeding the so-called transition current. Therefore, spray metal transfer is inevitably accompanied by high heat input and high weld penetration into the baseplate. As a result, the plate thickness and the welding position should be limited to some extent [**3**]. In addition, the high heat input and high weld penetration are usually considered to be extremely detrimental to deposition by welding [**6**] and other cladding applications [**10**].

In order to decouple the metal transfer process from the baseplate heating process, pulsed-current welding is introduced into the GMAW process [**9**–**11**]. By carefully controlling the waveform and the frequency of the pulsed

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current, the dependence of metal transfer on the mean welding current was greatly limited but still could not be completely decoupled. A more complete decoupling effect may be achieved by using independent power inputs such as a preheated wire-welding system, a welding gun with pulsed gas feeding, an additional electromagnetic field and an additional mechanical force [**12**]. It was reported that an appropriate electrode vibration could produce an additional mechanical force to shake droplets off the electrode, and the minimum current for welding of thin sheets could be reduced by 10–20 per cent compared with pulsed-current welding [**13**]. A few further results in this regard have also been reported [**14**]. In an attempt to apply the wire electrode vibration to the deposition by welding process, research work has been carried out at the Southern Methodist University Research Center for Advanced Manufacturing, and some of the experimental results are presented in this paper.

2 EXPERIMENTAL SET-UP AND PROCEDURES

In order to evaluate the effect of additional mechanical force in the GMAW process, a personal computer (PC)-controlled experimental welding system is developed. As shown in Fig. 1, this system integrates such functions as wire oscillation, precise control over the voltage and current, high-speed photography and motion control.

An oscillating wire feeder has been developed by the welding research group of the Harbin Institute of Technology [**12**]. It is designed to generate an additional force to cause detachment of the droplet. Thus, the projected transfer mode can be achieved much more easily. The oscillation can be activated by a stepping motor that is controlled by a single-chip computer. Through communication between the PC and the single-chip computer, the oscillating performance can be controlled. The oscillation behaviour is mainly defined by six parameters:

(a) the average feeding speed,
(b) the oscillation frequency,
(c) the forward velocity,
(d) the forward displacement,
(e) the backward velocity and
(f) the backward displacement.

The acceleration plays a key role in this process and is determined indirectly by these parameters. The oscillating wire feeder can reach a maximum vibration frequency of 150 Hz and can provide a maximum acceleration of 65*g*.

The wire electrode is driven by two clamping rolls, one of which is fixed to the shaft of a stepping motor. Two signals are used to control the stepping motor. The clockwise and the counterclockwise rotation are controlled with different parameters in order to improve the performance of the wire feeder. The oscillation is activated by the direction-control signal, and the displacement of the wire tip is measured with a displacement sensor as shown in Fig. 2. Based on the data of the wire-tip displacement, the velocity and acceleration can be calculated. Figure 3 shows the dynamic response of the welding wire tip, and the relationship between the wire-tip movement and droplet detachment is depicted in Fig. 4. During the forward motion of the wire, the wire tip is heated and melted, and the droplet grows to a certain size. When the wire tip abruptly changes the direction of motion (it moves backwards), a positive acceleration is generated and, thus, applies an additional

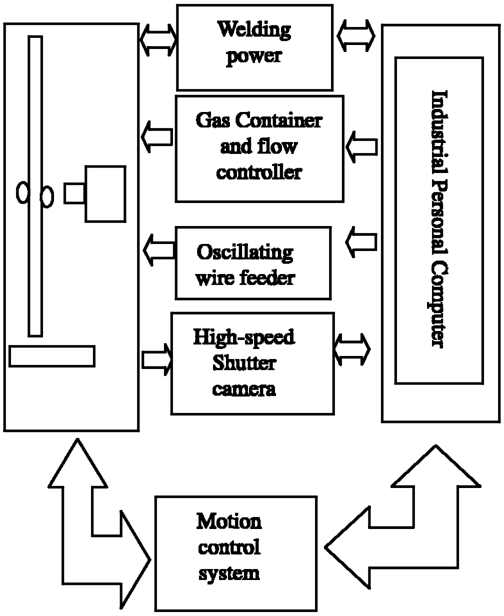


Fig. 1 Schematic diagram of the experimental set-up

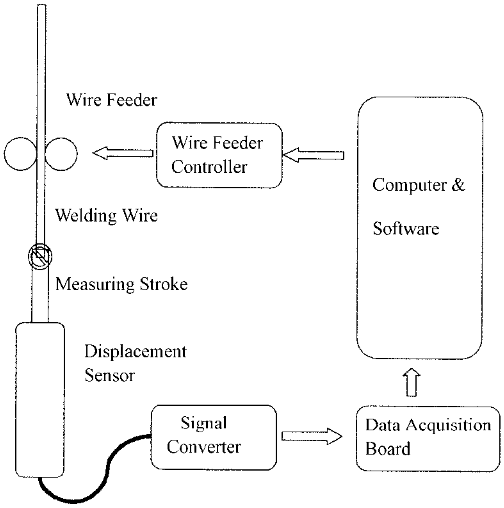
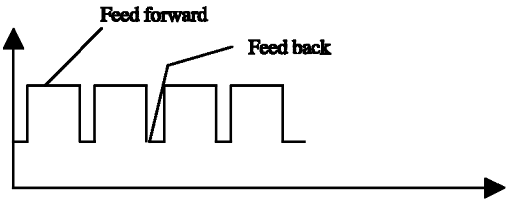
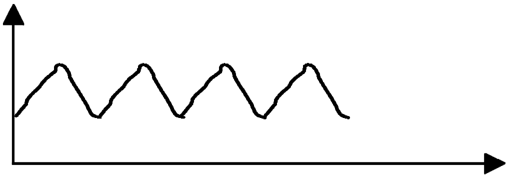


Fig. 2 Wire-tip motion-measuring device

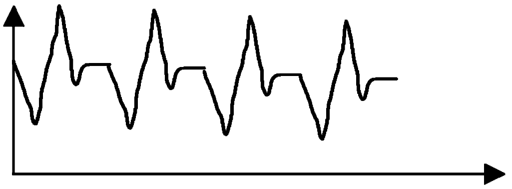


(a) Direction control



(b) Displacement of wire tip

(c) Velocity of wire tip



(d) Acceleration of wire

Fig. 3 Diagram showing the dynamic response of wire tip [**12**]

mechanical force (or energy) on the droplet to make it detach from the wire tip. In this process, the surface tension is the primary retaining force, which is related to the temperature, size and mass of the droplet as well as to the welding current and voltage applied. The gravitational force together with the additional mechanical force act as the detachment force. Figure 5 shows the result of the oscillating wire-feeder calibration and represents a good match between the droplet detachment and wire-tip movement.

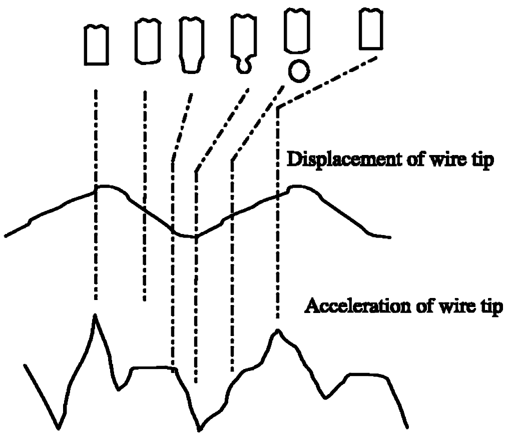


Fig. 4 Schematic diagram of wire oscillation and droplet transfer [**12**]

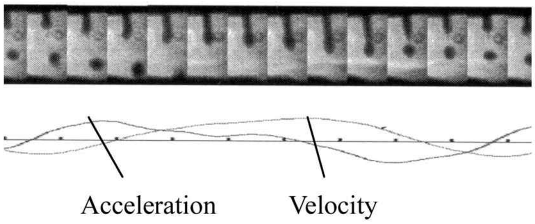


Fig. 5 Matching the droplet detachment with the wire-tip movement

With the development of welding technology, a number of sensing techniques have been used, e.g. sensing of airborne sound, sensing of welding arc voltage, sensing of arc light and high-speed photography. Compared with other methods, photography can directly provide information on the droplet-transfer rates and the droplet shapes. In this work, a high-frame-rate digital camera (up to 1000 frames/s) is used to obtain the images of the droplet detachment process in real time. A He–Ne laser is used as the back-lighting source.

The welding power source is operating in constant-current constant-voltage modes and it is controlled by the PC. The shielding gas is a mixture of argon (95 per cent) and CO_2 (5 per cent). In addition, a computer-controlled three-axis positioning system is used. The welding wire used for this work was made of ER70S-6 mild steel, with a diameter of 1.2 mm. The base metal plate was a low-carbon steel with dimensions of 105 mm × 25 mm × 6 mm. Two sets of bead-on-plate welding experiments were designed. One set was with a higher wire-feeding rate, 100 mm/s, and the other was with a lower wire-feeding rate, 60 mm/s. The wire oscillation frequency was set at four levels: 0, 40, 65 and 85 Hz. In both sets of experiments, the welding speed was fixed at 8.25 mm/s, and the shielding gas was delivered at a flowrate of 1.70 m^3/h. The distance between the gas nozzle tip and the base plate was maintained at 12 mm.

For the experiments operating at a wire-feeding rate of 100 mm/s, a series of welding currents were selected in the range 190–230 A in 10 A increments. For those with a wire-feeding rate of 60 mm/s, the welding current was varied over the range 130–180 A. In each experiment, the droplet-detachment process was imaged using the high-speed digital camera.

After the welding experiments, external macroscopic appearances of the weld beads were examined and the pictures were taken for comparison. Then, the metallographic samples of the weld cross-sections were prepared to examine the geometry of the weld beads and their microstructures.

3 RESULTS AND DISCUSSION

3.1 Characteristics of the droplet transfer process

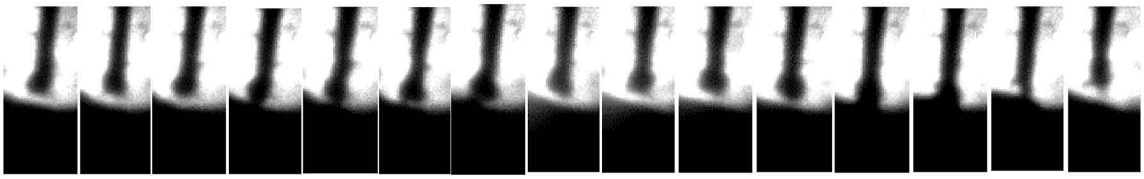
3.1.1 At a wire-feeding rate of 100 mm/s

Three aspects of the droplet transfer process are evaluated: the uniformity in droplet detachment, the droplet transfer rate and the droplet size. The uniformity in the droplet detachment is judged on the basis of image inspection. The droplet transfer rate and the droplet size are measured from the acquired images.

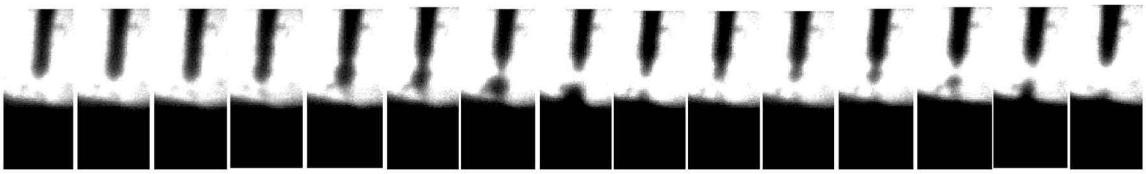
The droplet detachment process for welding at a wire-feeding rate of 100 mm/s and different wire oscillations is shown by the images in Fig. 6. The droplet transfer rate (the average number of droplets detached per second) and droplet diameter (averaged values) are plotted in Fig. 7 with respect to the welding current and the wire oscillation frequency. It can be seen that significant improvement in the droplet transfer process has been achieved by causing the wire electrode to oscillate.

For welding without wire oscillation, extremely low metal transfer rates ranging from 20 to 30 droplets/s are obtained when the welding current is below 220 A, and the corresponding droplet sizes are much larger than the diameter of the wire electrode (1.2 mm). Figure 6a reveals the process of a droplet detachment at 220 A. It can be seen that the droplet grows gradually at the tip of the wire electrode and is sustained there for a considerable time before contacting the weld pool and finally detaching. This is a typical mixture mode between short-circuiting and globular transfer. It is possible that much stronger short-circuiting effects could be seen at a lower current of 210 A. In fact, if there is no wire oscillation, acceptable welds cannot be formed when the welding current is reduced to less than 210 A.

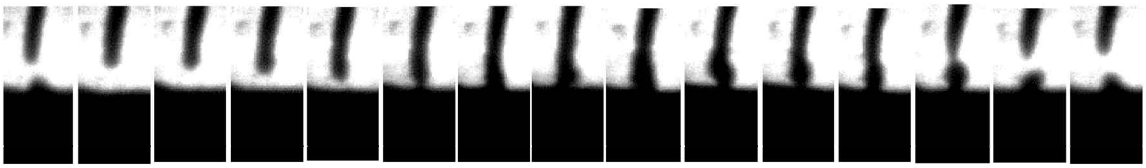
A significant transition in the rate of droplet detachment and in the size of droplets occurs between 220 and 230 A. As shown in Fig. 6b, a spray transfer mode is established when the welding current is increased to 230 A. Droplets with sizes comparable with the diameter of the wire electrode are sprayed from the wire tip to the weld pool at a rate of nearly 90 droplets/s. However, the spray transfer process is not sufficiently uniform. As shown by the last six frames of the images in Fig. 6b, some smaller droplets are usually observed to detach immediately following the normal-sized droplets. This process exhibits a characteristic of a short-term streaming transfer mode. The abruptness of the transition from the globular-dominated transfer to spray-dominated transfer



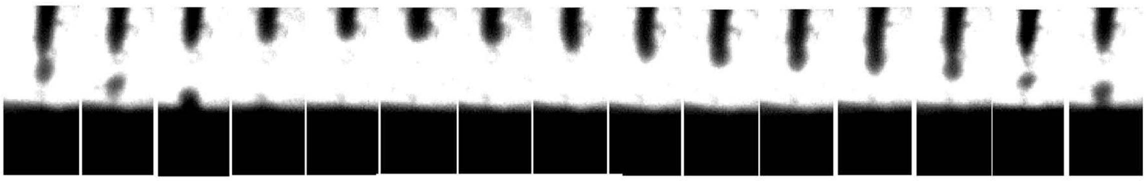
(a) 0 Hz, 220 A



(b) 0 Hz, 230 A



(c) 65 Hz, 220 A



(d) 85 Hz, 220 A

Fig. 6 Images of droplet detachment at a wire-feeding rate of 100 mm/s under different welding currents and different wire oscillation frequencies (839 frames/s)

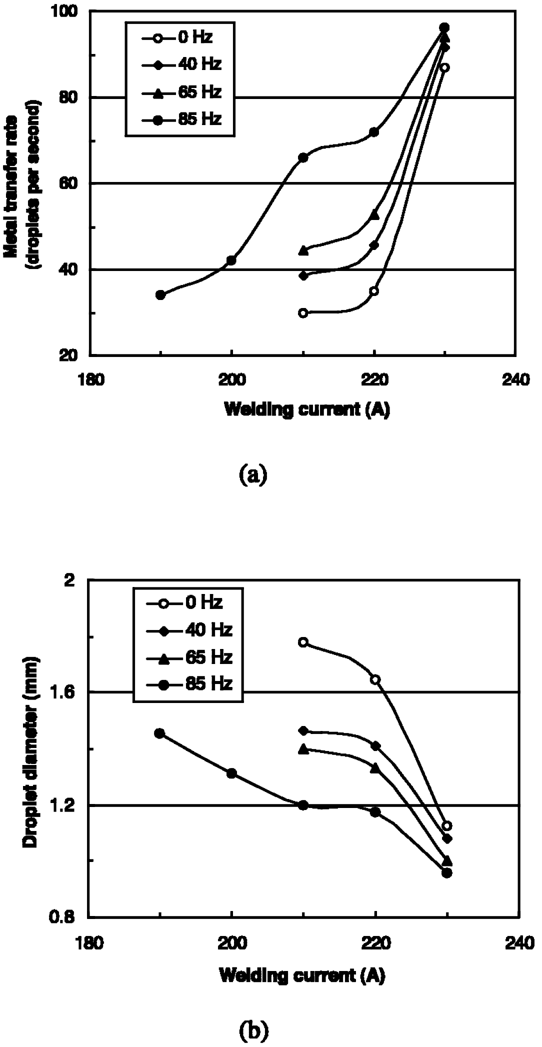


Fig. 7 Variations in (a) the droplet transfer rate and (b) the droplet size with welding current at a wire-feeding rate of 100 mm/s

has also been observed by Jones *et al.* [**15**] and Subramaniam *et al.* [**16**] and reported to be affected by the welding parameters, such as the properties of the wire and the gas composition [**17**].

As indicated in Fig. 7, by increasing the wire oscillation frequency, the droplet transfer rate increases even at the same welding current, and the droplet size decreases accordingly to be comparable with the diameter of the wire electrode, but the level of this improvement is quite dependent upon the oscillation frequency. Significant improvement can be achieved after the wire oscillation frequency reaches 85 Hz.

Figure 6c reveals a complete typical droplet transfer process at an oscillation frequency of 65 Hz and a welding current of 220 A. Although still in the mixture mode between the globular transfer and short-circuiting transfer, the cycle of the droplet formation and droplet detachment is greatly shortened, thus leading to an increased droplet transfer rate of 55 droplets/s. This value is nearly twice the transfer rate without wire oscillation. Meanwhile, the shape of the detached droplets becomes more regular and uniform than those produced without wire oscillation, as shown in Fig. 6a. This kind of beneficial effect can be ascribed to the additional mechanical force generated by wire oscillation. As shown by the images in Fig. 6c, the droplet grows while the wire tip moves downwards, and its volume becomes large enough to touch the weld pool surface when the wire tip begins to move upwards. As a result, the downward mechanical force resulting from the abrupt reverse of wire oscillation can further reinforce the detaching effect of the short-circuiting between the globular droplet and the weld pool.

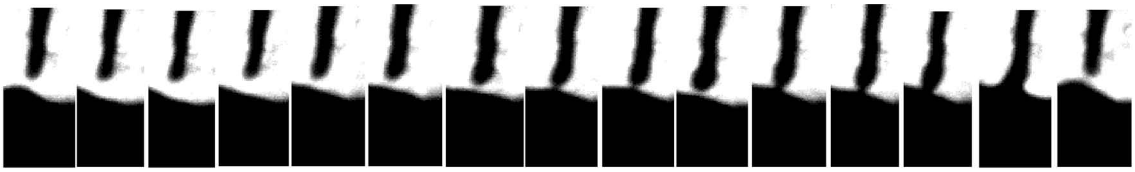
When the oscillation frequency is further increased to 85 Hz, a very satisfactory droplet transfer process can be obtained. As shown in Fig. 7, the droplet transfer rate reaches a relatively stable level of 70–80 droplets/s in the current range from 210 to 220 A. Meanwhile, the droplet size is almost equal to the diameter of the wire electrode. From the images shown in Fig. 6d, it can be seen that the droplet is very regular and uniform in shape and is detached from the wire tip in a typical spray (or projected) transfer mode. In addition, there is a good match between the wire oscillation stroke and the droplet detachment; i.e. each stroke of wire oscillation will produce one droplet. This result is very similar to the so-called one drop per pulse (ODPP), an ideal condition in pulsed gas metal arc welding [**9**]. This kind of droplet transfer is very stable and produces welds with minimal defects and spatter [**16**].

Unlike other oscillation frequencies used in this work, the 85 Hz wire oscillation can produce good welds at welding currents as low as 190 A. The corresponding droplet transfer rate and droplet diameter are also acceptable, as shown in Fig. 7. These phenomena can be attributed to the higher frequency of wire oscillation. By increasing the wire oscillation frequency, the molten metal has a higher chance of becoming detached from the wire tip, thus reducing the possibility of short-circuiting. In this work, where a relatively high wire-feeding rate of 100 mm/s was used, the highest oscillation frequency available at the wire feeder was 100 Hz. Our experimental work proved that the results with 100 Hz wire oscillation were very similar to those obtained at 85 Hz. It seems that there is no need to increase the wire oscillation frequency further.

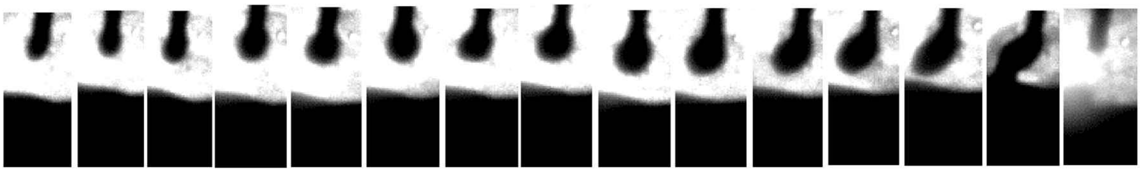
Also, it should be noted that very similar results are achieved at a higher current of 230 A for welding with and without wire oscillations. The rate of wire melting is increased, and the wire oscillation has less effect on the metal transfer process.

3.1.2 At a wire-feeding rate of 60 mm/s

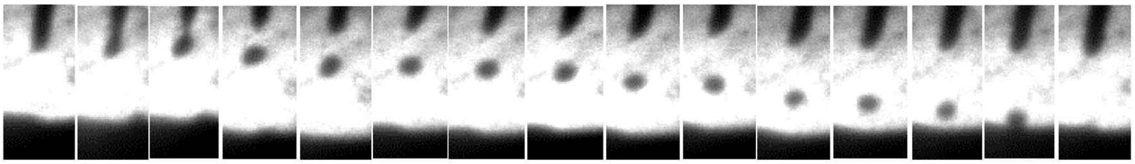
The droplet detachment process for welding at a wire-feeding rate of 60 mm/s is shown by the images in Fig. 8. The droplet transfer rate and the droplet diameter



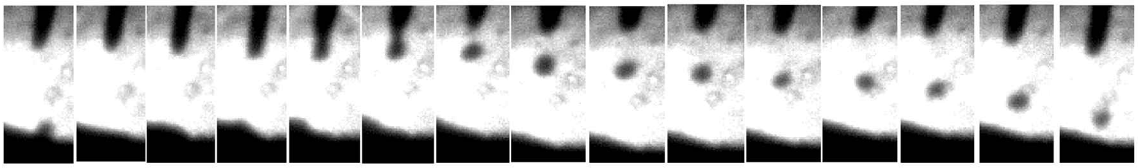
(a) 0 Hz, 140 A



(b) 0 Hz, 160 A



(c) 65 Hz, 160 A



(d) 85 Hz, 160 A

Fig. 8 Images of droplet detachment at a wire-feeding rate of 60 mm/s under different currents and different wire oscillation frequencies. [For (a) and (b), 420 frames/s; for (c) and (d), 839 frames/s]

are plotted in Fig. 9 with respect to the welding current and the wire oscillation frequency. It can be seen that significant improvement in the droplet transfer process has also been achieved by causing the wire electrode to oscillate.

For welds without wire oscillation, the droplet transfer rate decreases with increasing welding current (Fig. 9a), and the droplet size increases (Fig. 9b). This phenomenon is quite different from that observed at a higher wire-feeding rate of 100 mm/s. From the images shown in Fig. 8a, it can be seen that short-circuiting is the dominant transfer mode at currents up to 160 A, and globular growth is inhibited to some extent. This is mainly due to the low melting rate of the wire electrode resulting from the low wire-feeding rate and low welding current applied.

As reported by other researchers [**18**], the size of droplets and the frequency of droplet detachment are determined in essence by the forces exerted upon the droplet as well as by the electrode melting rate. When the current is increased to 160 A, a higher melting rate is induced and a globular transfer mode is established (Fig. 8b). In this case, the detaching electromagnetic force is still insufficient to detach the globules quickly, because of the low welding current [**15**, **16**]. Therefore, the droplet keeps growing and remains attached at the wire tip under the retaining effect of surface tension until it touches the weld pool and generates a short-circuiting pinch effect. This detachment process takes a much longer time than in the short-circuiting-dominated transfer process. Further increase in the welding current leads to a higher rate of wire melting, but the detaching forces are affected little, because even larger globular droplets are formed, as shown in Fig. 9b. As the distance of the wire extension was held constant at about 17 mm throughout the experiments, an excessive increase in the welding current would probably cause burning of the nozzle due to the inevitable increase in arc length; therefore the maximum current was fixed at 180 A in this set of experiments.

When wire oscillation is applied, a transition from the mixed short-circuiting and globular transfer modes to the spray transfer mode is obtained in the current range from 140 to 150 A, as shown in Fig. 9. For welding at an oscillation frequency of 65 Hz, the droplet transfer rate can be increased to over 45 droplets/s when the

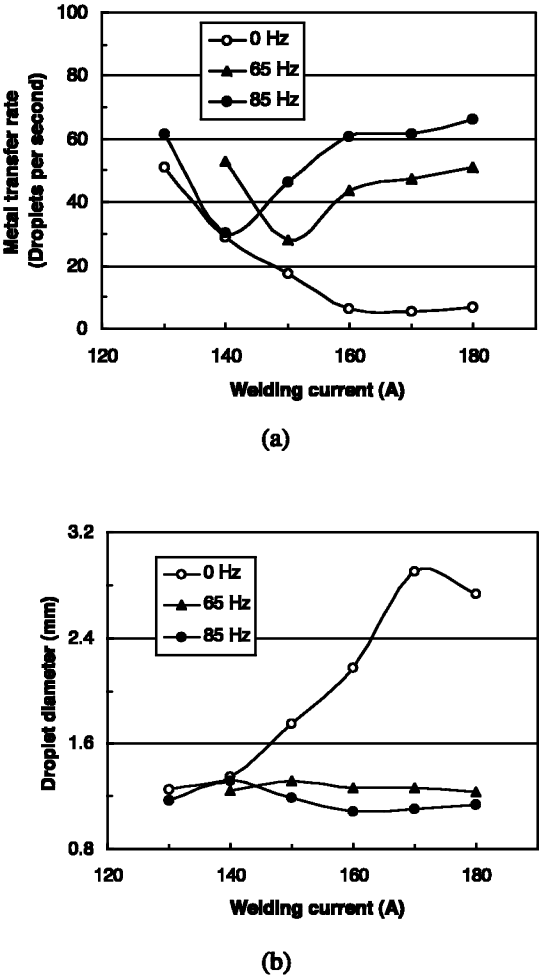


Fig. 9 Variations in (a) the droplet transfer rate and (b) the droplet size with welding current at a wire-feeding rate of 60 mm/s

welding current increases to 160 A. The rate tends to increase slowly when increasing the current further. Meanwhile, the corresponding droplet diameter can be maintained at about 1.3 mm, slightly larger than the diameter of the wire electrode. The images in Fig. 8c depict an entire process of droplet transfer. It can be seen that the droplet is very uniform in shape and the detachment is quite stable with the help of the additional mechanical force generated by the wire oscillation. In each cycle of wire oscillation, the molten metal detaches from the wire tip shortly after the oscillating stroke is reversed upwards.

For welding at an oscillation frequency of 85 Hz, the droplet transfer rate can be as high as 60–70 droplets/s when the current is increased to 160 A and above, and the droplet diameter becomes slightly smaller than the diameter of the wire electrode. Uniform droplets are detached from the wire tip on the basis of one drop per stroke, as indicated in Fig. 8d.

From the above experimental results, it can be concluded that wire oscillation can greatly improve the droplet transfer process in GMAW. For welding at a high wire-feeding rate of 100 mm/s, more obvious improvements can be achieved at currents below 220 A. By contrast, for welding at a low wire-feeding rate of 60 mm/s, more significant improvements are obtained at currents above 160 A. In addition, the higher the oscillation frequency, the greater is the improving effect. However, there are always narrow gaps between the oscillation frequencies and the resultant droplet transfer rates. In order to achieve an ideal condition of one drop per stroke, just like ODPP in pulsed GMAW [**10**, **11**], further work should be carried out to optimize the complex parameters of welding process and wire oscillation.

3.2 Surface quality of the weld beads

3.2.1 Welds produced at a wire-feeding rate of 100 mm/s

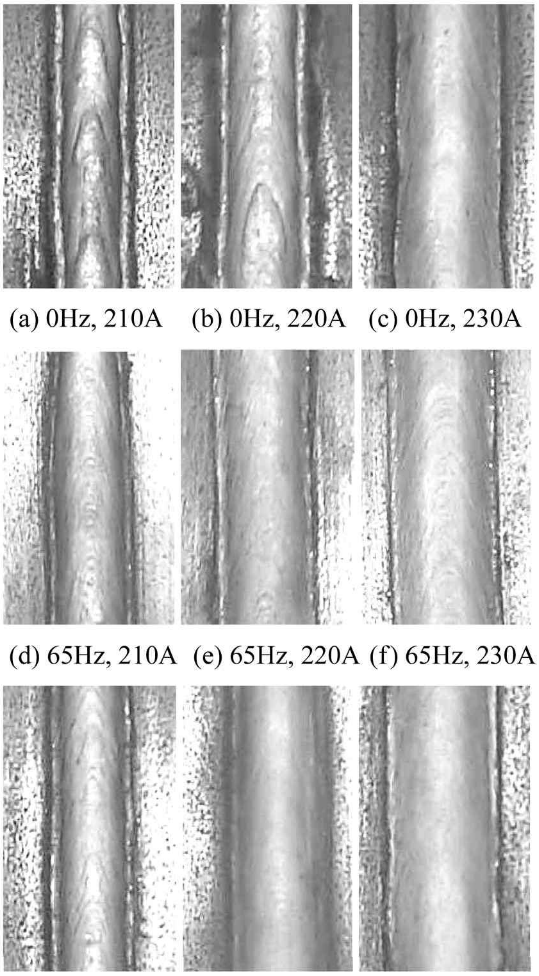
Three aspects of the surface quality of the weld beads are evaluated: the uniformity of the bead along the direction of welding, the smoothness of the bead surface and the severity of spattering. Figure 10 shows the weld beads produced at a high wire-feeding rate of 100 mm/s. It can be clearly seen that the application of wire oscillations in welding has significantly improved the surface quality of the weld beads.

For welding at 210 A without wire oscillation, the weld is not uniform and is extremely uneven, with many ripples on the surface (Fig. 10a). This result corresponds to the mixing mode of short-circuiting and globular transfer that is intrinsic to the unstable process of violent detachment and spattering [**19**]. By increasing the welding current to 220 and 230 A, the weld becomes more uniform and smoother (Figs 10b and c). This phenomenon is mainly attributed to the increase in the droplet transfer rate and the decrease in the droplet size as well as to the improvement in the fluidity of the weld pool [**3**]. However, since the spray transfer is mixed with the short-term streaming transfer as indicated earlier in Fig. 6b, the weld bead produced at 230 A is still not uniform enough.

In comparison, for welding with a 65 Hz wire oscillation, the weld beads are somewhat better than those obtained at the same current without wire oscillation (Figs 10d, e and f). It has also been found that the best weld with a smooth uniform spatter-free appearance is achieved at a current of 220 A.

Furthermore, for welding with an 85 Hz wire oscillation, the best welds can be obtained in the current range 210–220 A (Figs 10h and i), and an acceptable weld is also achieved at a much lower current of 200 A.

The beneficial effect of wire oscillation on the surface quality of the weld beads is closely related to the improvement in the droplet transfer process demonstrated in the above sections. The additional mechanical force generated by the wire oscillation helps to make the molten metal detach as droplets from the wire tip, thus


(a) 0Hz, 210A (b) 0Hz, 220A (c) 0Hz, 230A

(d) 65Hz, 210A (e) 65Hz, 220A (f) 65Hz, 230A

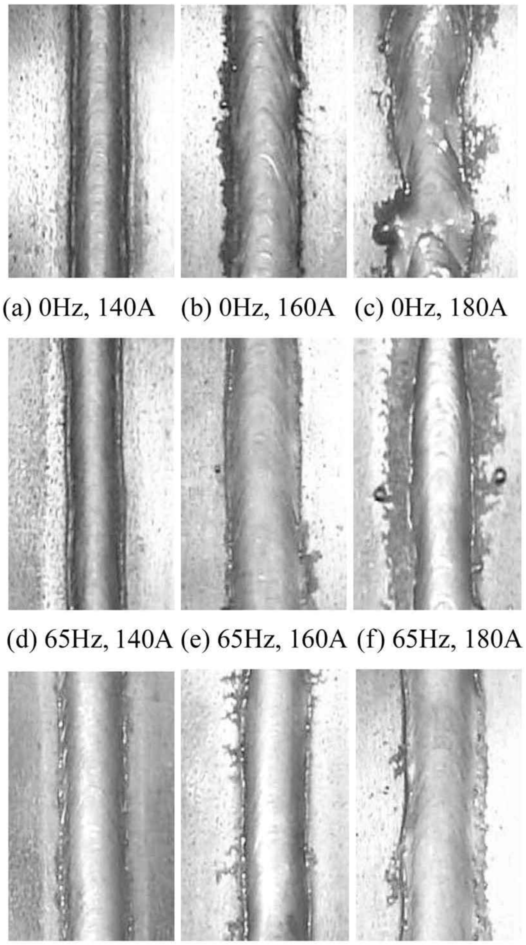
(g) 85Hz, 200A (h) 85Hz, 210A (i) 85Hz, 220A

Fig. 10 Macroscopic appearance of the weld beads produced at a wire-feeding rate of 100 mm/s under different welding currents and different wire oscillation frequencies

leading to a projected spray transfer process, just like that observed in pulsed GMAW [**10**]. The present experimental results have verified that the projected spray transfer process provided with the help of wire oscillation can produce even better weld surfaces than the conventional spray transfer process. More importantly, the projected spray transfer condition can be established at lower welding currents than conventional spray transfer. This kind of condition will evidently lead to less induced heat in the workpiece, and this outcome will be very beneficial for rapid prototyping based on deposition on welding as well as for the welding of thin gauges.

3.2.2 Welds produced at a wire-feeding rate of 60 mm/s

Figure 11 shows the weld beads produced at a low wire-feeding rate of 60 mm/s. It can be seen that all the welds have been reduced in width compared with those produced at a higher wire-feeding rate of 100 mm/s. In addition, wire oscillation produces better weld surfaces.


(a) 0Hz, 140A (b) 0Hz, 160A (c) 0Hz, 180A

(d) 65Hz, 140A (e) 65Hz, 160A (f) 65Hz, 180A

(g) 85Hz, 140A (h) 85Hz, 160A (i) 85Hz, 180A

Fig. 11 Macroscopic appearance of the weld beads produced at a wire-feeding rate of 60 mm/s under different welding currents and different wire oscillation frequencies

For welding without wire oscillation, a uniform but narrow weld can be achieved only at a low current of 140 A (Fig. 11a), where a short-circuiting transfer mode dominates. On increasing the current to 160 and 180 A, the uniformity of the weld bead degrades so much that no acceptable weld can be produced at 180 A (Figs 11b and c). This is in accordance with a decreased droplet transfer rate and an increased droplet size.

For welding with a 65 Hz wire oscillation, the corresponding welds become much better at each current level (Figs 11d, e and f), but the weld produced at 180 A still has some spatter, most probably because an occasional mini-explosion is induced during the droplet detachment process caused by short-circuiting.

For welding with an 85 Hz wire oscillation, all the welds produced in the current range 140–180 A are of quite good surface quality (Figs 11g, h and i). This result can be ascribed to a stable and uniform droplet transfer process.

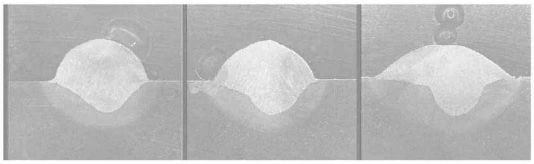
Compared with the effects of wire oscillation at the high wire-feeding rate of 100 mm/s, wire oscillations at the low wire-feeding rate of 60 mm/s appear to be more effective in improving the surface quality of welds when a wider range of welding currents are applied.

3.3 Cross-sectional profiles of the weld beads

For quantitative evaluation of the weld bead geometry, such parameters as weld penetration P, reinforcement height H, weld width W, bead-plate wetting angle and fusion angle are usually determined [**3**]. In the case of conventional welding, desirable weld characteristics should include a larger depth of penetration, a larger weld width, a high percentage of dilution, a larger fusion angle, less height of reinforcement and a smaller bead-plate wetting angle [**3**]. In the case of welding-based overlay cladding or deposition applications, however, the least possible penetration and dilution are required to obtain uniform microstructures and properties as well as to reduce the heat input [**10**].

Figure 12 shows the cross-sectional profiles of the weld beads obtained at a wire-feeding rate of 100 mm/s with and without wire oscillation. It can be seen that the geometry of the weld beads produced with wire oscillation is much more uniform and regular than those developed without wire oscillation. More importantly, even at the same level of welding current, the weld width increases significantly while the reinforcement height and the bead-plate wetting angle as well as the cross-sectional area of penetration decrease. As a result, a satisfactory weld bead can be obtained at much lower currents if wire oscillation is employed in welding. Therefore, it can be concluded that wire oscillation can offer geometrical advantages to the GMAW process and make it very suitable for applications to a large area of overlay cladding and to deposition processes.

Figure 13 shows the cross-sectional profiles of the weld beads obtained at a wire-feeding rate of 60 mm/s. It can be seen that small weld beads are produced in this condition, and that the geometries of the weld beads are also modified to a great extent with wire oscillation. In fact, welding deposition is based on small weld beads in order to guarantee the dimensional accuracy during layer-by-layer build-up. In particular, the weld beads with low reinforcement form factors W/H tend to produce heavily distorted walls after three or four passes of overlay build-up [**9**]. Therefore, wire oscillation can be a very practical way to solve these problems.


(a) 0Hz, 210A (b) 0Hz, 220A (c) 0Hz, 230A

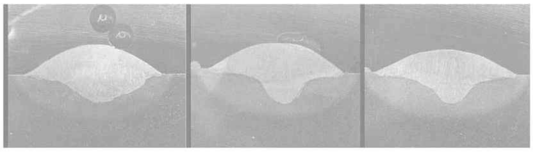

(d) 85Hz, 200A (e) 85Hz, 210A (f) 85Hz, 220A

Fig. 12 Cross-sectional profiles of the weld beads produced at a wire-feeding rate of 100 mm/s under different welding currents and different wire oscillation frequencies


(a) 0Hz, 140A (b) 0Hz, 160A (c) 0Hz, 180A

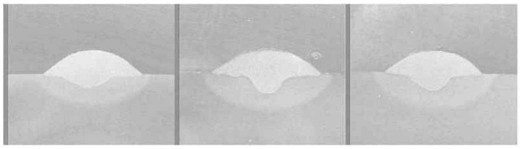

(d) 85Hz, 140A (e) 85Hz, 160A (f) 85Hz, 180A

Fig. 13 Cross-sectional profiles of the weld beads produced at a wire-feeding rate of 60 mm/s under different welding currents and different wire oscillation frequencies

Summing up the above experimental results, it is apparent that wire oscillation can improve the droplet transfer process in GMAW and induce a projected spray transfer mode at reduced welding current levels. The projected spray transfer process produces a very stable uniform detachment of small droplets at considerably high rates, thus giving rise to high-quality weld beads that are most suitable for overlay cladding and rapid prototyping.

4 CONCLUSIONS

1. The additional mechanical force resulting from wire electrode oscillation can make the droplet size smaller and produces a higher droplet transfer rate, thus greatly improving the droplet transfer process in GMAW.
2. For welding at a higher wire-feeding rate, 100 mm/s, a significant improvement in the weld quality is achieved for welding currents ranging between 210 and 220 A. However, for a wire-feeding rate of 60 mm/s, an acceptable weld quality is obtained for the welding currents ranging from 160 to 180 A.
3. The wire oscillation frequency plays a key role in improving the droplet transfer process. The higher the oscillation frequency, the greater is the improving effect. In this work, 85 Hz oscillation yielded the best effect where a projected spray transfer mode was established and a very stable uniform detachment of small droplets are achieved.

4. The improved droplet transfer process with wire oscillation helps to produce weld beads of high surface quality with a uniform smooth spatter-free appearance. High surface quality of weld beads is of significant importance for overlay cladding and rapid prototyping based on deposition by welding.
5. With wire oscillation, the geometry of the weld beads can be modified considerably. The weld width increases significantly while the reinforcement height and the bead-plate wetting angle as well as the cross-sectional area of penetration decrease.

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