Bead formation and wire temperature distribution during **ULTRA-HIGH-SPEED GTA WELDING** using pulse-heated hot-wire

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ABSTRACT

The melting of filler wire is investigated in detail to obtain the precise temperature distribution of the filler wire during ultra-high-speed gas tungsten arc (GTA) welding and develop ultra-high-speed GTA welding with a pulse-heated hot-wire system for three kinds of materials. The melting phenomena of the filler wire were observed using a high-speed camera, and temperature distributions of the filler wire were measured using a radiation thermometer. The results show that ultra-high-speed GTA welding can be achieved with suitable welding conditions for each material. Ultra-high-speed GTA welding requires suitable wire current to obtain a suitable temperature distribution and melting position of the filler wire. Moreover, the temperature distributions of three kinds of filler wire could be estimated using a proposed simple estimation method.

IIW-Thesaurus keywords: GTA welding; Hot; Wire, High; Speed; Temperature.

1 Introduction

There has been recent, strong demand for high-speed welding with high economical efficiency (e.g. laser welding and high-speed gas metal arc welding) to reduce the construction cost of welded structures, especially in automotive manufacturing [1, 2]. Although gas metal arc welding has the advantages of convenience and economic efficiency when compared with laser and gas tungsten arc (GTA) welding, the welding speed is limited by high arc current, which results in defects and burn through when thin plates are welded at high speed up to around 2 m/min [3, 4]. There are also problems with laser welding; e.g. high initial costs and small gap tolerance. GTA welding has many advantages, but its speed and deposition rate are much lower than those for other welding processes.

Hot-wire GTA welding has been developed to improve the deposition rate through heating of the filler wire [5]. Hori *et al.* proposed and developed hot-wire GTA welding using pulsed current to heat the filler wire and solve problems such as magnetic arc blow and arcing from the wire [6-10]. The developed pulse-heated hot-wire GTA welding has been applied mainly in thick plate welding to obtain much higher efficiency than is possible for previously established welding processes. Shinozaki and Yamamoto *et al.* developed ultra-high-speed GTA welding based on the above hot-wire system using type 304 stainless steel material (JIS SUS304) [11-16]. In their studies, the phenomenon of filler wire melting was observed and the filler wire temperature was measured under an ultra-high welding speed condition. As a consequence, the basic effects of different welding parameters on the welding phenomenon under the ultra-high welding speed condition have been obtained, and it has become clear that the wire temperature (wire current) is the most important parameter in achieving ultra-high-speed GTA welding. Welding speeds up to 7 m/min under the bead-on-plate condition and 5 m/min under the fillet welding condition have been achieved.

The purpose of this study is to apply the developed ultra-high speed GTA welding to the other materials (mild steel and Ti). Melting of the filler wire is observed in detail using a high-speed camera and the temperature distribution of the filler wire is precisely measured using a radiation thermometer during welding at ultra-high speed to clarify the requirements for welding in the case of each material. Moreover, a simplified method for estimating the filler wire temperature distribution is proposed to obtain the suitable wire current easily under various welding conditions and for various materials before performing ultra-high-speed GTA welding.

2 Experimental procedure

Tables 1, 2 and 3 show the chemical compositions of three kinds of base plates and filler wire used in this study. This study considers a mild steel plate (JIS SPHC) of 2.3 mm

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Table 1 – Chemical compositions of the mild steel plate and filler wire [wt. %]

Materials	C	Si	Mn	P	S	Cu	Al	Ti+Zr
JIS SPHC (2.3 mm^t)	$<$ 0.15	--	$<$ 0.6	$<$ 0.05	$<$ 0.05	--	--	--
JIS Z3321YGW11 (Ø 1.4 mm)	0.04	0.68	1.55	0.014	0.013	0.03	$<$ 0.01	0.23

Table 2 – Chemical compositions of the Ti plate and filler wire [wt. %]

Materials	C	H	N	O	Fe
JIS H 4600-2001 TP340C (3 mm^t)	$\leq$ 0.08	$\leq$ 0.013	$\leq$ 0.03	$\leq$ 0.20	$\leq$ 0.25
JIS Z3331 (Ø 1.2 mm)	0.01	0.0039	0.01	0.10	0.06

Table 3 – Chemical compositions of the stainless steel plate and filler wire [wt. %]

Materials	C	Si	Mn	P	S	Ni	Cr
JIS SUS304 (2 mm^t)	0.06	0.47	0.76	0.029	0.001	8.00	18.00
JIS Z3321Y308 (Ø 1.4 mm)	0.05	0.40	1.89	0.012	0.010	9.56	20.45

thickness and filler wire (JIS Z3321 YGW11) of 1.4 mm diameter given in Table 1, a Ti plate (JIS H4600-2001 TP340C) of 3 mm thickness and filler wire (JIS Z3331) of 1.2 mm diameter given in Table 2, and a type 304 stainless steel plate (JIS SUS304) of 2 mm thickness and filler wire (JIS Z3321 Y308) of 1.4 mm diameter given in Table 3.

Figure 1 shows the sizes and configurations of the specimens used in the tests. Bead-on-plate welding was performed and the wire temperature distribution was measured and the melting of the wire observed to determine suitable welding conditions of each material in ultra-high-speed GTA welding.

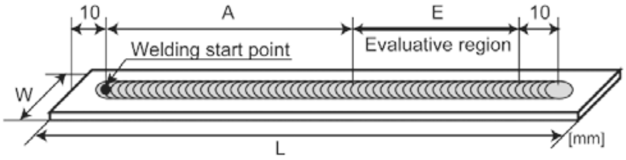
Table 4 shows the welding conditions for each material investigated in the present study. The welding speed was fixed as 3 m/min and the wire feeding rate was changed to fix the wire feeding amount per unit length as shown in Table 4. The wire current was varied as the main parameter in the ultra-high-speed GTA welding according to the electrical resistance of each material. A tungsten electrode of 3.2 mm diameter was used, and the torch angle and wire feeding angle were fixed as 90° and 30°, and the arc length as 1 mm.

The bead appearance was taken as the evaluation criterion to judge weldment quality in this study. A bead without any surface defect (e.g. a pit or hole) within an evaluation region, as shown in Figure 1, was judged as a sound bead, whereas a bead with any surface defect within the evaluation region was judged as a faulty bead.

The wire melting phenomenon at the filler wire tip was observed in detail using a high-speed camera (Photoron FASTCAM-1024PCI) with a resolution of

Table 4 – Welding conditions

Material	Mild steel	Ti	Stainless steel
Welding speed, V [m/min]	3		
Wire current (R.M.S.), Iw [A]	202 ~ 220	96 ~ 124	161 ~ 186
Wire feeding speed, Vw [m/min]	6.6	8.9	6.6
Wire feeding amount [m^3/m]	3.4×10^{-6}		
Wire feeding angle [°]	30		
Pulse frequency of wire current [Hz]	100		
Duty of pulsed wire current [%]	50	30	50
Arc current, Ia [A]	250	300	250
Arc length [mm]	1		
Shielding gas rate [l/min]	14 (Ar)		



Materials	W	L	A	E
Mild steel	50	400	180	170
Ti	100	200	90	70
Stainless steel	50	400	180	170

Figure 1 – Sizes and configurations of specimens

1 024 × 1 024 pixels and a 950 ± 5 nm band-pass filter without lighting. A frame speed of 125 or 250 fps was employed in high-speed imaging.

Figure 2 shows the experimental set-up for the temperature measurement of the filler wire, and measurement points of the filler wire temperature are indicated in the figure. A radiation thermometer with a spot diameter of 0.6 mm (Japan Sensor FTZ6-R300-20L12) was used to measure the filler wire temperature precisely during high-speed feeding. The emissivity of the filler wire used in this study was measured using a high-frequency heating apparatus to calibrate the radiation thermometer before the test [11-13].

3 Test results and discussion

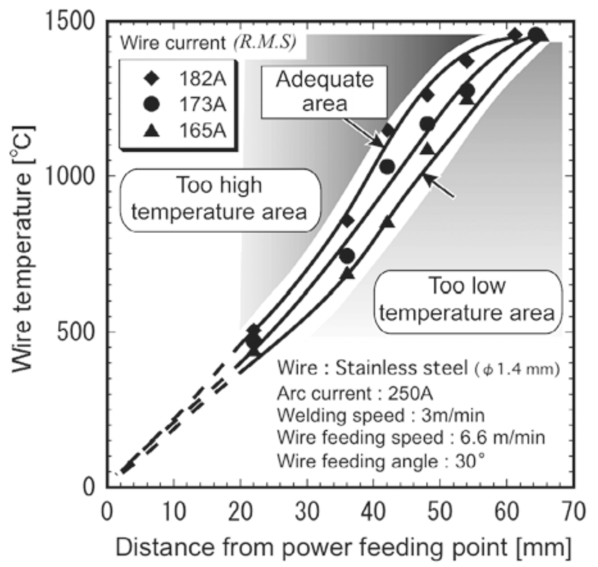


Figure 3 – Temperature distribution of the filler wire from the power feeding point (stainless steel)

Figure 3 shows the temperature distributions of the stainless steel filler wire when the wire current was varied as a parameter for a welding speed of 3 m/min, arc current of 250 A and wire feeding rate of 6.6 m/min. The temperature distributions of the stainless steel filler wire were measured at wire currents of 165, 173 and 182 A (root-mean-square values of pulsed current). Figure 4 shows the high-speed imaging outputs and bead surfaces when the wire current was varied from 162 to 186 A. It is clear from Figures 3 and 4 that the welding was adequate (defect-free) within the range of wire current from 165 to 182 A, and typical defects (e.g. discontinuous beads or pits) were seen on the bead surface when the wire current either exceeded 182 A or was less than 165 A. When the wire current was 186 A, the high-speed imaging outputs show that the filler wire excessively softened and the tip of the wire was intermittently in contact and not in contact with the molten pool. In addition, there was spattering, and the melting position of the filler wire was far from the centre of the electrode because of the too high wire temperature. On the other hand, when the wire current was 162 A, the high-speed imaging outputs show that the tip region of the filler wire did not melt properly and the filler wire bumped the bottom of the molten pool because of the too low wire temperature. The position of wire melting was directly below the centre of the electrode. When the wire current was within the suitable range from 165 to 182 A, the melting of the filler wire was adequate. Figure 3 shows that the tip of the filler wire started melting near the molten pool and was stably in contact with the molten pool when the wire current was suitable. In other words, the melting position of the filler wire was within the limited proper range near the molten pool and had a suitable temperature.

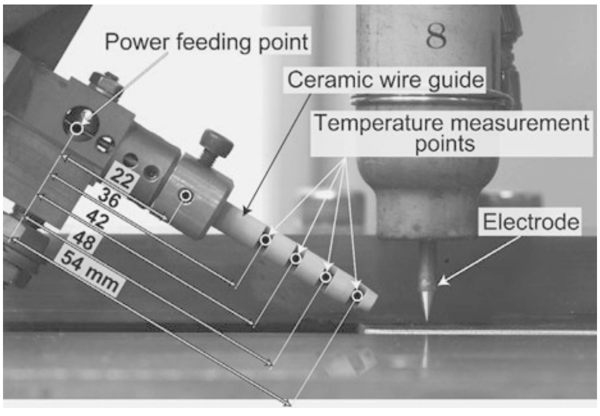


Figure 2 – Experimental set-up for temperature measurement of the filler wire

It is clear from the above results for the stainless steel filler wire that there are three ranges of temperature of the filler wire (adequate, too high and too low temperature ranges) in the ultra-high-speed welding, and it was necessary to heat the filler wire within an adequate suitable range to achieve proper ultra-high-speed welding and produce high-quality beads without defects. It is also clear from the high-speed imaging outputs (Figure 4) that an increase in the wire current increases the distance between the wire melting position and centre of the electrode, and the filler wire needs to be heated to a suitable temperature and the wire melting position needs to be within a limited region near the molten pool to achieve steady ultra-high-speed welding.

Figure 5 shows the temperature distributions of mild steel filler wire when the wire current was varied as a parameter for a welding speed of 3 m/min, arc current of 250 A and wire feeding rate of 6.6 m/min. The temperature distributions of mild steel filler wire were measured at wire currents of 204, 210 and 215 A (root-mean-square values of pulsed current). Figure 6 shows the high-speed imaging outputs and bead surfaces when the wire current was varied from 202 to 222 A. It is clear from the test results for mild steel that there were three ranges of the filler wire temperature (adequate, too high and too low temperature ranges) in the ultra-high-speed welding of mild steel, as in the case of stainless steel. When the wire current was

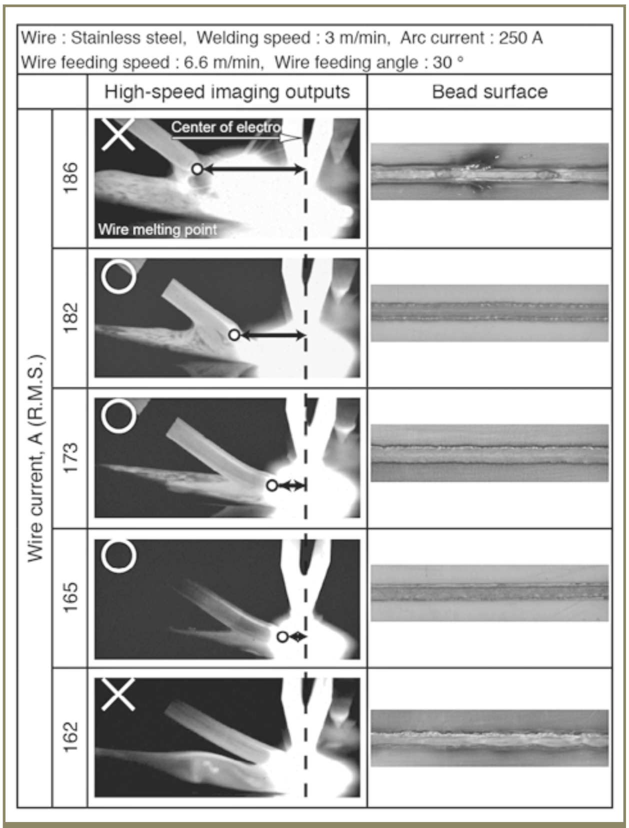


Figure 4 – High-speed imaging outputs and bead surfaces (stainless steel)

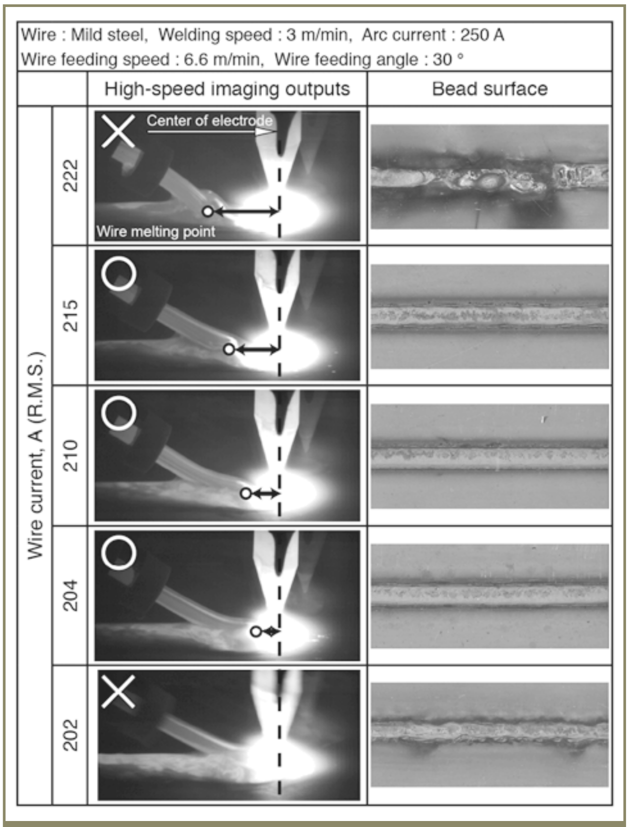


Figure 6 – High-speed imaging outputs and bead surfaces (mild steel)

within a suitable range from 204 to 215 A, there was stable melting of the filler wire and the tip of the filler wire was in stable contact with the molten pool. When the wire current was 222 A, the tip of the filler wire was intermittently in contact and not in contact with the molten pool, and defects (spatters and pits) were observed owing to excessive heating and softening of the filler wire. When the wire current was 202 A, the tip of the filler wire did not melt before coming into contact with the molten pool, and pits constantly formed because the unmelted filler wire tip pressed into the bottom of the molten pool. The above results indicate that ultra-high-speed GTA welding can be applied to mild steel having relatively low electrical resistance by adjusting the wire current to an appropriate value, which is higher than that for stainless steel shown in Figure 3.

Figure 7 shows the temperature distributions of the Ti filler wire when the wire current was varied as a parameter for a welding speed of 3 m/min, arc current of 300 A and

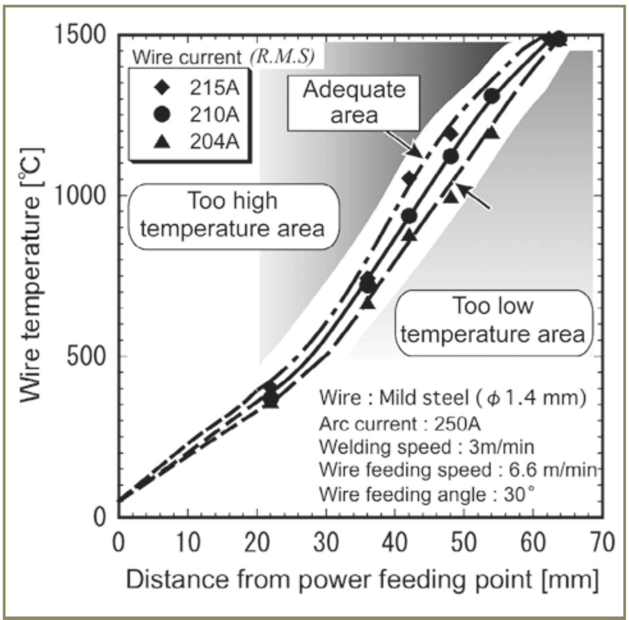


Figure 5 – Temperature distribution of the filler wire from the power feeding point (mild steel)

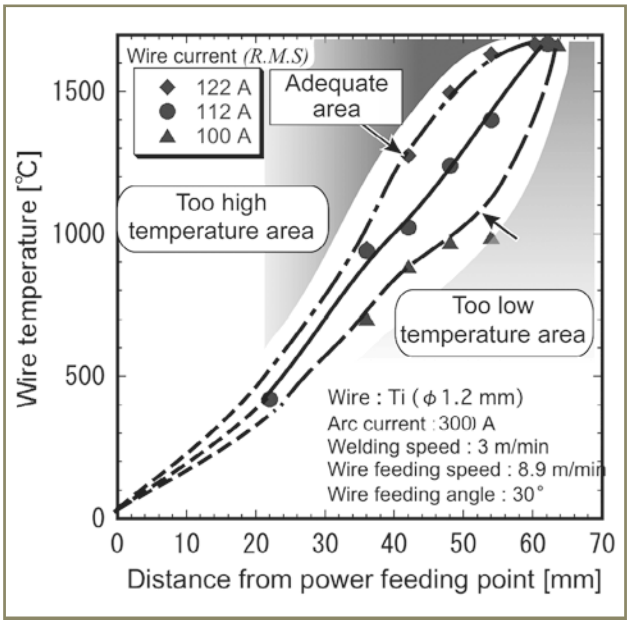


Figure 7 – Temperature distribution of the filler wire from the power feeding point (Ti)

wire feeding rate of 8.9 m/min. The temperature distributions of the Ti filler wire were measured at wire currents of 100, 112 and 122 A (root-mean-square values of pulsed current). Figure 8 shows the high-speed imaging outputs and the bead surfaces when the wire current was varied from 96 to 126 A. Figure 7 shows that although there were again three ranges of the filler wire temperature (adequate, too high and too low temperature ranges) in the ultra-high-speed welding of Ti material, the shape of the temperature distribution of the Ti filler wire differed from those of stainless steel and mild steel filler wire since Ti has properties of temperature-dependent specific heat and electrical resistance that greatly differ from those of stainless steel and mild steel. When the wire current was within a suitable range from 100 to 122 A, the tip of the filler wire was in stable contact with the molten pool and sound beads were created without defects. When the wire current was 96 A, the too low temperature of the filler wire resulted in pits on beads because the tip of the filler wire did not melt properly and pressed into the bottom of the molten pool. When the wire current was 126 A, although the tip of the filler wire was intermittently not in contact with the molten pool, defects (spatters and pits) were not seen, apparently because the Ti filler wire had greater stiffness at higher temperature than other materials and did not excessively soften. It is clear from the above results that ultra-high-speed GTA welding can also be applied to Ti having relatively high electrical resistance by adjusting the wire current to a proper value, which is lower than those for stainless steel and mild steel.

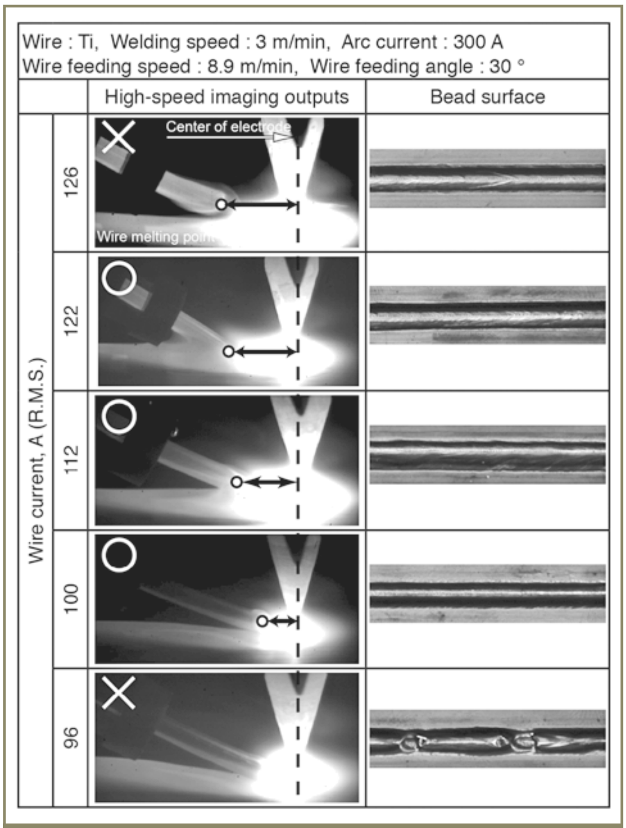


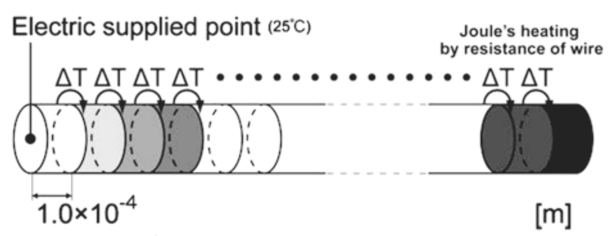
Figure 8 – High-speed imaging outputs and bead surfaces (Ti)

4 Method for estimating the distribution of the filler wire temperature

In this study, a simplified estimation method of the filler wire temperature distribution was investigated to obtain the suitable wire current easily under various welding conditions (e.g. welding speed, wire feeding rate, filler wire material and filler wire diameter) before performing ultra-high-speed GTA welding. Joule heating dependent on the electrical resistance of the filler wire, Joule heating of the contact resistance at the electrical feeding point and heat transfer from the filler wire heated during feeding are considered in the proposed estimation method.

Figure 9 is a schematic illustration of the estimation method for the filler wire temperature distribution during steady feeding. The temperature increment was calculated per 0.1 mm in the heating length (64 mm) considering temperature-dependent material properties of the electrical resistivity, specific heat capacity and density (see Figure 10). Joule's heating due to the contact resistance at the electrical feeding point was added to the Joule's heating of the filler wire in the contact region from 0 to 5 mm.

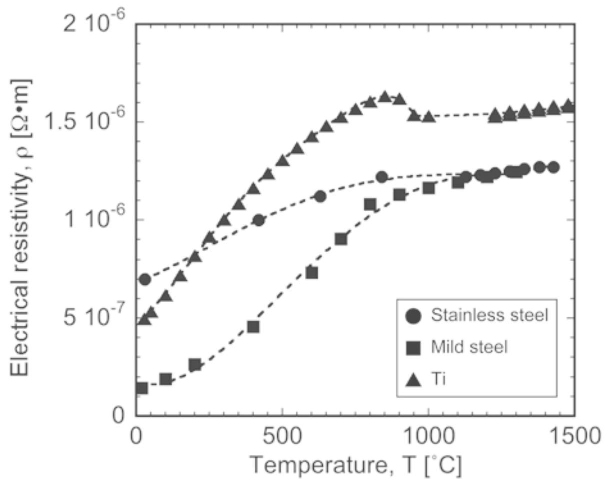
Figures 11, 12 and 13 show the estimated temperature distributions for each material and wire current. The figures show good agreement between the distributions estimated using the proposed simplified calculation method and experimental results for all materials and wire currents. In other words, the suitable wire current, for obtaining a suitable temperature distribution in ultra-high-speed GTA welding, can be estimated for various materials and welding conditions using the proposed simplified estimation method and temperature-dependent material properties of each material.



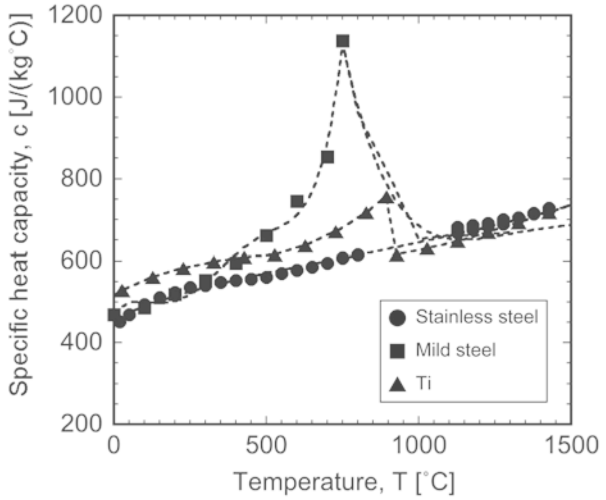
$\Delta T = [R(T) \times I^2 \times t] / [c(T) \times m(T) \times V]$

T : Temperature at the calculated region of the filler wire
R(T) : Temperature-dependent electrical resistivity
c(T) : Temperature-dependent specific heat
m(T) : Temperature-dependent density
I : Wire current
t : Heating time through a region (0.1mm)
V : Volume of a region

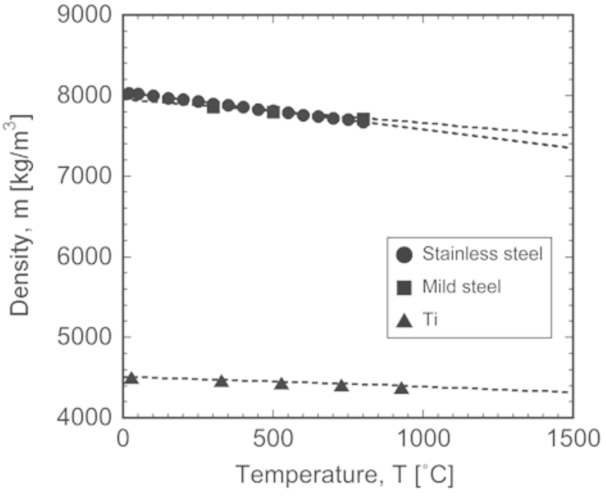
Figure 9 – Schematic diagram of the estimation method for the temperature distribution of the filler wire



a) Temperature-dependent electrical resistivity



b) Temperature-dependent specific heat capacity



c) Temperature-dependent density

Figure 10 – Material properties for estimation of temperature distributions of the filler wires

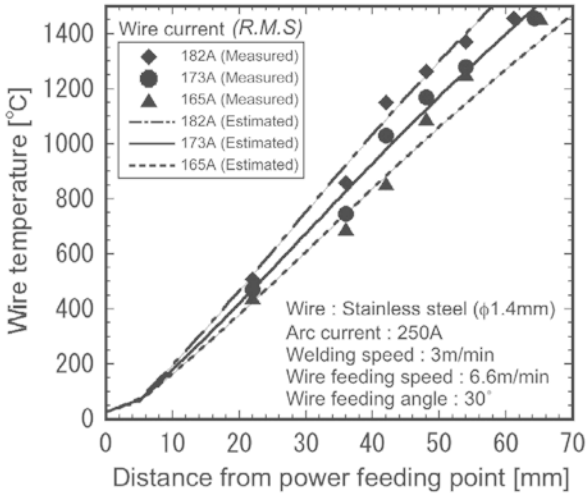


Figure 11 – Estimated temperature distributions of the filler wire (stainless steel)

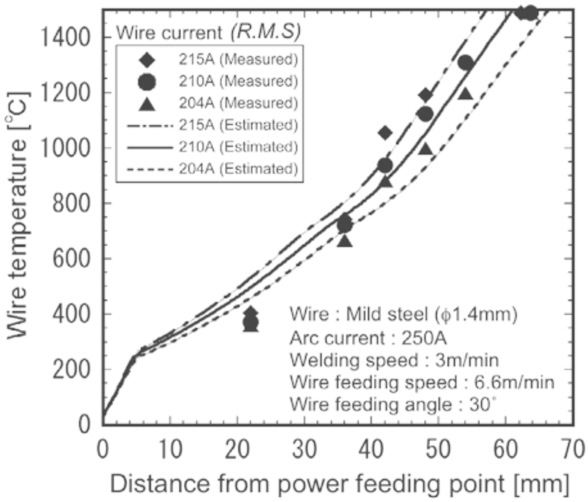


Figure 12 – Estimated temperature distributions of the filler wire (mild steel)

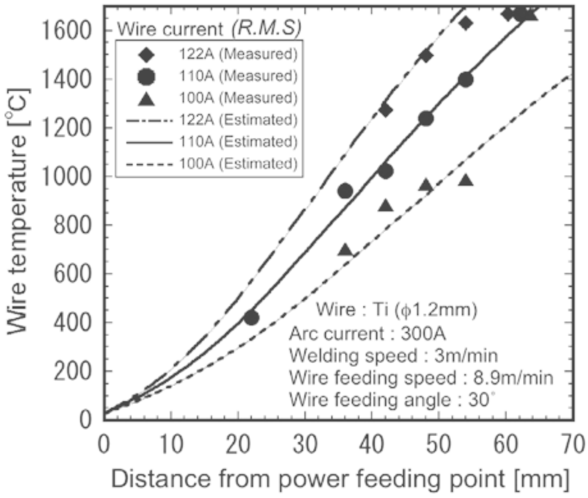


Figure 13 – Estimated temperature distributions of the filler wire (Ti)

5 Conclusions

Ultra-high-speed GTA welding using a pulse-heated hot-wire system was investigated by observing the wire melting phenomenon in detail with a high-speed camera and by measuring the wire temperature distribution using a radiation thermometer for mild steel, Ti and stainless steel. Furthermore, a simplified estimation method of the filler wire temperature distribution was proposed to obtain the suitable wire current easily for various welding conditions and various materials. The results of this study are summarized as follows.

1. The temperature distribution and melting position of the filler wire have a decisive effect on the ultra-high-speed GTA welding phenomenon and weld quality for all investigated materials (stainless steel, mild steel and Ti). The filler wire needs to be heated within a suitable range for a certain material and the melting position of the filler wire needs to be within a proper region to achieve proper welding.
2. Ultra-high-speed GTA welding can be applied to stainless steel, mild steel and Ti materials having various electrical resistances by adjusting the wire current to a proper value according to the respective electrical resistance. Moreover, there are three ranges of the filler wire temperature (adequate, too high and too low temperature ranges) for all materials, and typical defects occur when the wire temperature (current) is too high or too low.
3. The suitable wire current for obtaining a suitable temperature distribution in ultra-high-speed GTA welding can be estimated for all materials and welding conditions employing the proposed simplified estimation method and temperature-dependent material properties of each material.

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