

Unique characteristics of the novel-GTAW process for the butt joint of ultra-thin silicon steel sheets

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Abstract

Butt joining of ultra-thin silicon steel sheets is a major challenge because of the ultra-thin thickness, high silicon content, and the coating layer on their surfaces. For the first time, welding butt-joint of the 0.2 mm ultra-thin silicon steel sheets has been performed successfully and reported in this paper. The results show that the weld beads fabricated by the novel-GTAW process are straight, stable, and without defects. They have a narrower width on the top and a larger width on the bottom side compared to the conventional-GTAW process. The mechanical properties of the welding joints also overmatch that of the base metal, confirming good qualities of the weldment. The success of the novel GTAW process in butt weld of ultra-thin silicon steel sheets is because of its unique characteristics: First, the mechanism of the novel-GTAW torch allows removing and blowing the insulation coating layer to prevent its penetration into the melting point and its accumulation on the electrode during the welding process; thus, eliminating welding defects and electrode wear and maintaining the arc stability. Second, the novel-GTAW process enables superiorly reducing the heat input and increasing the cooling rate, which ensures the high quality of the butt weld of ultra-thin silicon steel sheets. Lastly, the shielding efficiency of the melting pool is enhanced to prevent silicon oxidation and welding defects.

Keywords: Novel-GTAW process; unique characteristics; butt joint; ultra-thin sheet; silicon steel.

1. Introduction

Ultra-thin silicon steel sheets with magnetic properties [1] and a thickness of 0.08 – 0.3 mm [2] are widely utilized in manufacturing the stator/rotor core of electrical motors, transformers, and power generation [3]. In the current rotor/stator production lines, a new coil will be replaced when a raw material coil is run out. This stage takes much time as the production line must be stopped for more than 30 minutes [4]. Moreover, an enormous amount of raw material needs to be cut throughout to avoid defect products. To deal with this problem, the butt joint of raw material coils while the line is still operating becomes an ideal approach.

However, the butt welding of ultra-thin silicon steel sheets is a major challenge for the current welding technologies. Silicon steel is a special alloy with a high percentage of silicon [5]. The surfaces of silicon steel sheets are usually covered by an insulation layer with a thickness of 3-10 μm [6], which is made of forsterite (Mg_2SiO_4) combined with resins or silica [7]. This layer is nonconductive and consists of many elements that have negative effects on the weldability. They can also react to other elements in the melting pool and base metal during the welding process to raise defects and heterogeneity.

It is well known that the welding current in the fusion welding processes is formed between the anode (i.e., tungsten electrode or consumable wire) and the cathode (i.e., substrate or base metal) [8]. In the welding of silicon steel sheets, due to the non-metallic insulation layer on their surfaces, it is difficult to discharge the arc plasma and maintain a stable current during the welding process. Moreover, the vapor of elements from the insulation layer can penetrate in the melting pool, leading to welding defects (e.g., porosity and brittle fracture). The vapor of the insulation layer can also enclose the tungsten electrode during the welding process, causing a rapid burning and wearing. Thus, the lifespan of the tungsten electrode is significantly reduced.

Additionally, the silicon with a high percentage in silicon steel sheets easily reacts to the oxygen from the air and causes defects such as porosities, brittle cracks, and weld bead surface oxidation [9,10]. In this case, a welding process with a shielding gas flow having an effective effect on the melting pool is expected. However, this is difficult to ensure by a conventional-GTAW process because of its low shielding efficiency [11,12]. Furthermore, because of having a very thin thickness (0.08 – 0.3 mm) [13,14], the welding of ultra-thin silicon steel sheets easily makes defects, such as burn-through. Consequently, controlling the heat input to avoid excessive thermal bending, thermal accumulation, and burn-through is another challenge.

To deal with this issue, the laser welding (LW) process would be an alternative selection, because the nozzle does not directly contact the welding pool and the base metal. **(II-2)** Moreover,

the LW process has high energy density, small spot size, and high-welding velocity [15]. In the welding of electrical steels, the continuous LW process enabled achieving better magnetic characteristics compared to the arc fusion welding [16,17]. However, laser welding systems are complex and high cost as compared and reported in [18]. These systems also have rigorous safety requirements [19,20]. **(II-3)** Several published works have demonstrated that the micro-plasma arc (μ PTA) [18,21] and friction stir welding (FSW) [22–24] processes can be applied to weld ultra-thin metal sheets. Nevertheless, to the best authors' knowledge, there are not yet publications, which uses these processes to successfully butt weld ultra-thin silicon steel sheets.

As a conclusion, there are many risks and difficulties in the butt weld of ultra-thin silicon steel sheets. Until now, no welding processes have successfully applied to this kind of material. Therefore, the development of a novel welding process for this task is essential. In our previous work [4], we have developed a novel-GTAW technology for the butt weld of ultra-thin metal sheets. We have demonstrated that the novel-GTAW process efficiently welded the butt joint of ultra-thin SUS 304 sheets with a thickness of 0.03 mm and 0.25 mm. Compared to the welding process of SUS 304 steel, the welding of silicon steel is much more challenging.

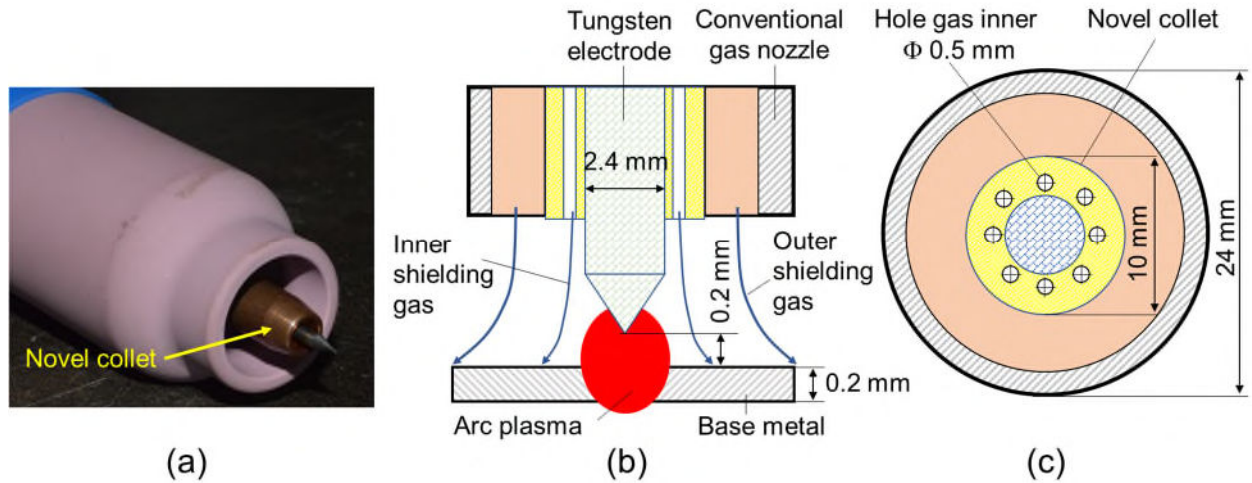
In this article, we aim at demonstrating that the novel-GTAW process with its unique characteristics can be successfully applied for the butt joint of ultra-thin silicon steel sheets. For that purpose, a series of experiments have been performed on silicon steel sheets of 0.2 mm in thickness. The bead weld appearance, microstructural and mechanical characteristics of the welded samples were observed to prove the superior efficiency of the novel-GTAW process.

2. Materials and methods

2.1. Welding equipment, materials, and welding conditions

Fig. 1b and 1c describe the schema of the novel-GTAW torch (Fig. 1a). A new collet is attached to the torch. The eight holes with a small diameter of 0.5 mm were manufactured by drilling alongside the collet body. The collet is contacted the tungsten electrode. **(II-12)** It was a little bit of a change in the structure of the novel-torch compared to ref [4]. This is because we are developing this process, the torch used in ref [4] is hard to manufacture and machining, therefore, an innovative structure was performed. However, it was verified by our experiments that both torches have not changed the principle and efficiency.

The experimental conditions are presented in Table 1. The silicon steel sheets (supplied by JFE Corporation, Japan) with dimensions of 0.2 $\times$ 500 mm $\times$ 100 mm (thickness $\times$ width $\times$ length) were used. The chemical composition of silicon steel is composed of 3.2% Si, 0.0048% C, 0.001% P, 0.0019% S, 0.0014% Al, and balanced Fe (in wt.%) [5]. As aforementioned, the silicon steel sheets are challenging to weld because of the non-conductive and insulation coating layers.



(II-12) Fig. 1. (a) The real novel torch and its schema: (b) longitudinal section (schematic only), (c) cross-section (schematic only).

A welding machine (100A-ST, Daihen corporation) and a 2.4-mm-diameter tungsten electrode were used. An angle of 45 degrees was ground for the electrode tip. The distance between the electrode's tip and the surface of the base metal was 0.25 mm. The welding speed and the peak welding current were set up at 50 mm/s and 24 A, respectively. The argon with 99.99% of purity was used for the torch gas, novel collet gas, and back shielding gas. The flow rate of torch gas, novel collet gas, and back-shielding was 5.0, 3.0, and 2.5 L/min, respectively.

Table 1. Welding conditions.

Parameters	Specific
Welding system (Daihen corporation)	100A-ST
Raw material (leading and trailing)	Silicon steel grade
Size of the raw material (length × width × thickness)	(II-4) 100 mm×500 mm×0.2 mm
Current waveform	Pulse DCEN
Peak current	24 A
Bead current	8 A
Welding pulse frequency	120 Hz
Welding speed	50 mm/s
Shielding gas outer (Ar)	5 L/min
Back shielding gas (Ar)	3 L/min

Novel collet gas inner (Ar)	2.5 L/min
Arc length	0.2 mm
Tungsten electrode	2.4 mm
Electrode tip angle	45 ⁰

2.2. Study on the appearance of the tungsten electrode wear and weld beads

To observe the effect of the electrode wear on the weld bead quality, 3 similar electrodes were used in the experiment for each welding process – i.e., the novel-GTAW process and the conventional-GTAW process. The shape of electrode and the appearance of the weld bead was observed after 20 s, 40 s, and 80 s of welding by an optical microscope (VHX-D600, Keyence, Japan). The appearance and the width of weld beads were also examined on both the top and bottom sides by the same optical microscope.

In fact, with the welding speed of 50 mm/s and the substrate width of 500 mm, one welding seam can be finished after 10 s. Therefore, to observe the tungsten electrode wear after 20 s of welding in the novel- or the conventional-GTAW process, the first new electrode was utilized for two welding seams (the length of each welding seam is 500 mm). Afterwards, the first electrode was removed for the electrode wear observation, and the second new electrode was inserted and performed other 4 welding seams. Subsequently, the second electrode was removed to observe its wear status after 40 s of welding. Similarly, the third new electrode was used for 8 welding seams to inspect its wear after 80 s of welding.

2.3. Microstructure, microhardness, and tensile tests

Once the tests to observe the performance of the novel- and conventional-GTAW processes to butt weld the silicon steel sheets finished, only the novel-GTAW butt welded samples were taken to examine the internal quality and the welding joint strength. The metallographic samples were prepared to analysis the microstructure of the novel-GTAW weldment. The microstructure was analyzed using an electronic scanning microscope (SEM), SU-70. The grain size was estimated from the microstructure image using ImageJ software.

A Vickers hardness machine (Mitutoyo MicroWizhard) was utilized to measure the microhardness. A load of 980.7 mN and a dwell time of 15 s were applied for each indentation. Three measurement lines were defined corresponding to the top zone, the middle zone, and the bottom zone of the weldment cross-section (Fig. 2). The microhardness was measured at 24 points distributed on each measurement line crossing the base metal zone (BMZ), heat-affected zone (HAZ), and welded metal zone (WMZ).

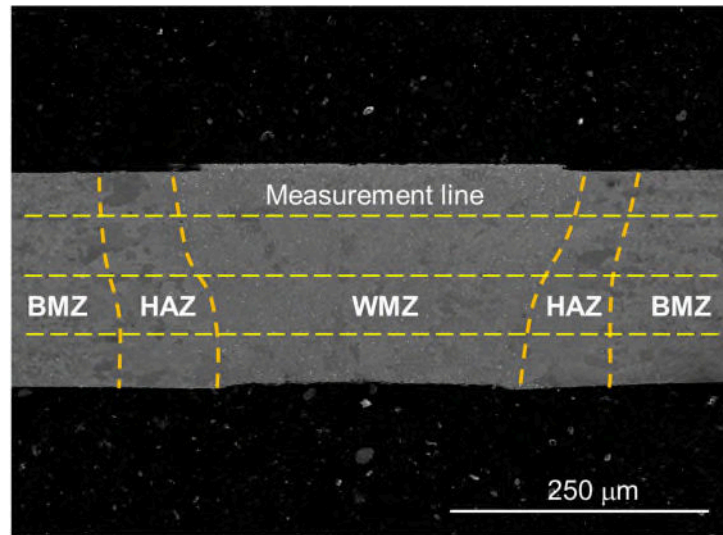


Fig. 2. The zones and lines for measuring the microhardness of the welding sample produced by the novel GTAW process.

The tensile strength of the novel-GTAW weldment was also tested. **(II-5)** The shape of tensile samples is designed according to the ASTM standard (E8/E8M –13a). However, the instruction for cutting the ultra-thin sheets of 0.2 mm is not clear. Furthermore, those sheets are easy to cut by a handle cutting device. Therefore, the five straight tensile samples with dimensions of $0.2 \times 20 \times 200$ mm (thickness $\times$ width $\times$ length) and the weldment located at their center were prepared. These samples were tested by a tensile tester (Instron 5500R, Japan).

3. Experiment results

3.1. Appearance of weld beads

Fig. 3 presents the bead appearance at 10 s of welding in both the novel- and the conventional-GTAW processes. It is revealed that the novel-GTAW weld bead (Fig. 3b) is straighter, stable, and looks much better than that obtained by the conventional-GTAW process (Fig. 3a).

The width of the novel-GTAW bead is 1.23 mm on the top side and 0.86 mm on the bottom side. On the other hand, the bead fabricated by the conventional-GTAW process has a width of 1.28 mm and 0.72 mm on the top and the bottom side, respectively. Moreover, welding defects such as undercuts and slags (e.g., silicon oxidation) can be observed on the conventional-GTAW weld bead (Fig. 3a).

Fig. 4 shows the half cross-sections of weld seams fabricated by the conventional-GTAW process (Fig. 4a) and the novel-GTAW process (Fig. 4b). It is also indicated that the novel-GTAW process produced a smaller width on the top and a larger width on the bottom compared to that produced by the conventional-GTAW process. The difference in width between the top side and

the bottom side in the novel-GTAW process was significantly reduced compared to that in the conventional-GTAW process (about 59%).

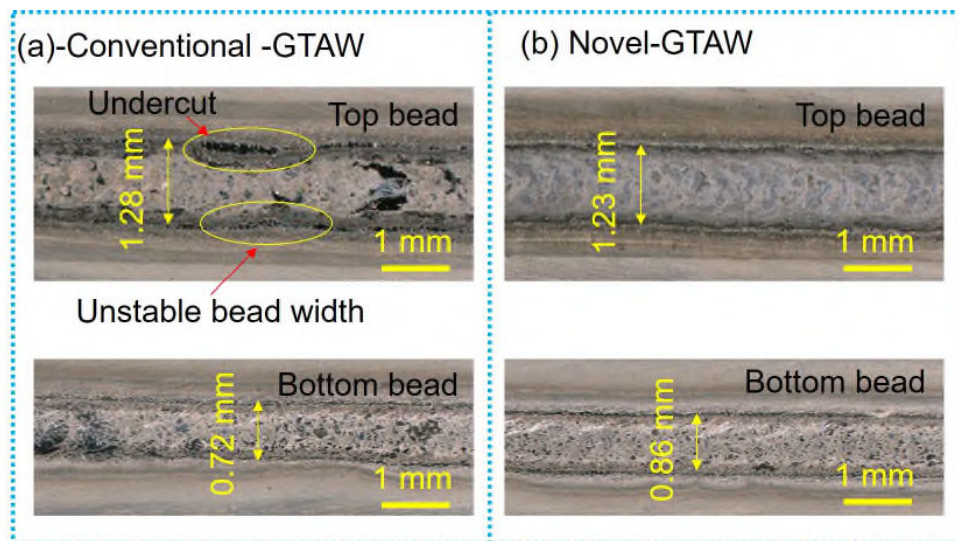
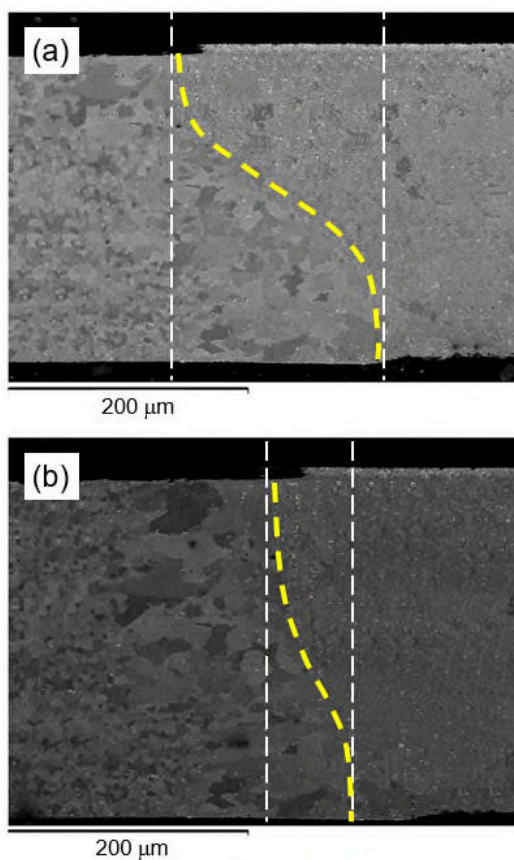
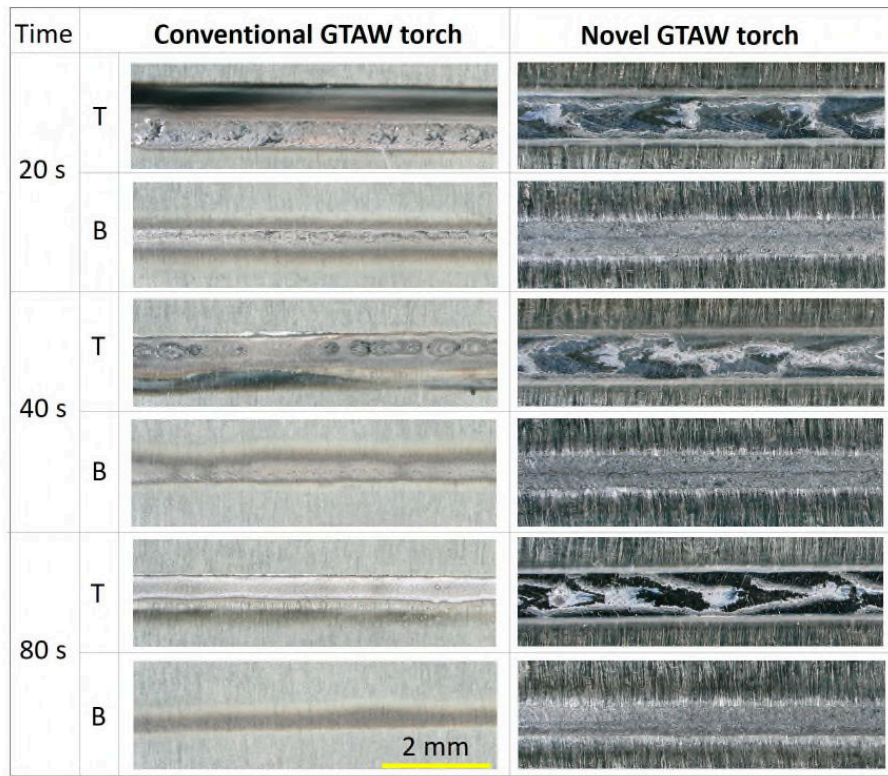


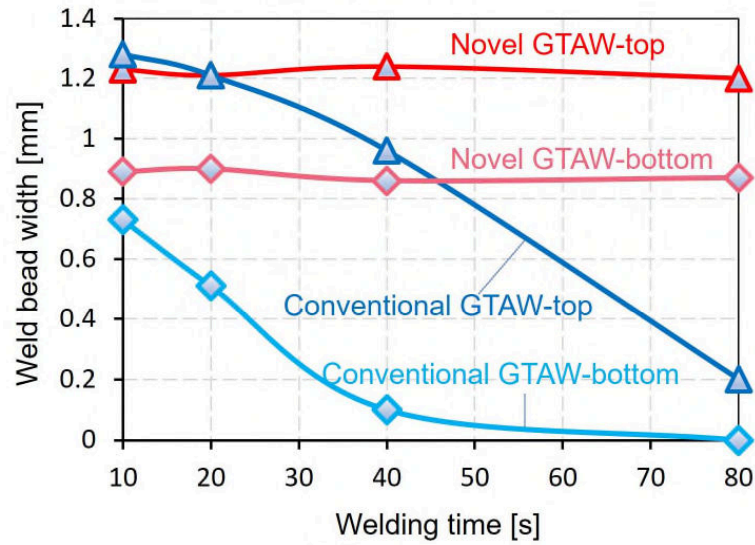
Fig. 3. The bead appearance at 10 s of welding by (a) conventional-GTAW process and (b) novel-GTAW process.



(II-6) Fig. 4. Half cross-section of the weld seam fabricated by (a) the conventional-GTAW and (b) the novel-GTAW processes at 10 s of welding.



(a) Bead appearance



(b) Bead appearance

(II-9) Fig. 5. (a) The weld bead appearance (in which, T is the top surface and B is the bottom surface) and (b) the comparison of bead width following the time.

Fig. 5 portrays the weld bead appearance and its width comparison following the time. The bead width obtained by the novel-GTAW process is nearly unchanged, with a slight deviation. The weld bead width on the top and bottom sides were maintained about 1.20 ~ 1.23 mm and 0.85 ~ 0.93 mm, respectively. Meanwhile, the bead width achieved by the conventional-GTAW process dropped sharply after 10 s of welding. After 20 s of welding, the width on the bottom of the weld bead was equal to two thirds of that at the 10th second. Finally, the bead width reached zero at the

80th second. Similarly, the top bead width was dropped from 0.91 mm at the 40th to 0.2 mm at the 80th second. This means that no welding process was done from the 40th second for the conventional-GTAW process. **(II-9)** This result suggests that the conventional-GTAW process is impossible to weld this material. And all results about tensile strength and hardness following will be done for only novel-GTAW process.

3.2. Tungsten electrode wear

The tungsten electrode situation in both cases of the novel-GTAW and conventional-GTAW processes is shown in Fig. 6. There is a clear difference between the conventional-GTAW process and the novel process. Before the welding, the electrode was ground with the same tip angle in both cases. After the welding, the electrode tip was sharply worn in the conventional-GTAW process (Fig. 6b). Meanwhile, it was quietly stable and gradually worn in the novel process (Fig. 6a).

Compared to the original electrode shape, the amount of the electrode wear in the novel-GTAW torch was about 0.11 mm, 0.15 mm, and 0.16 mm at the 20th, 40th, and 80th second, respectively, while the electrode wear was about 0.28 mm, 0.77 mm, and 0.99 mm at the 20th, 40th, and 80th second, respectively, in the conventional-GTAW process (Fig. 6c). The tungsten was also necked quickly. At the 40th second, the globule part of the electrode tip was dropped into the molten pool (Fig. 6b). On the other hand, the contamination on the electrode surface seems to be rare in the novel-GTAW torch (Fig. 6a).

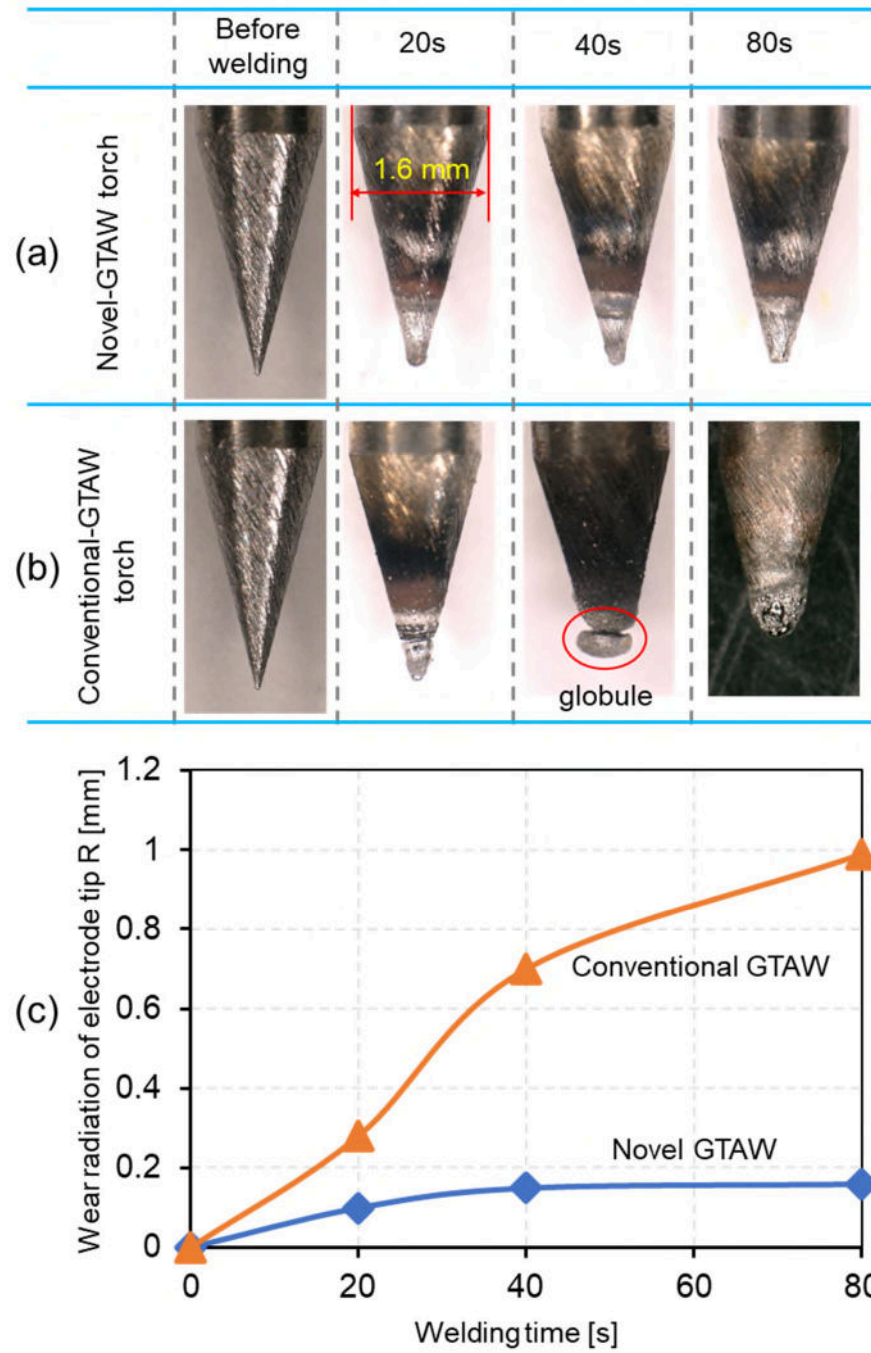
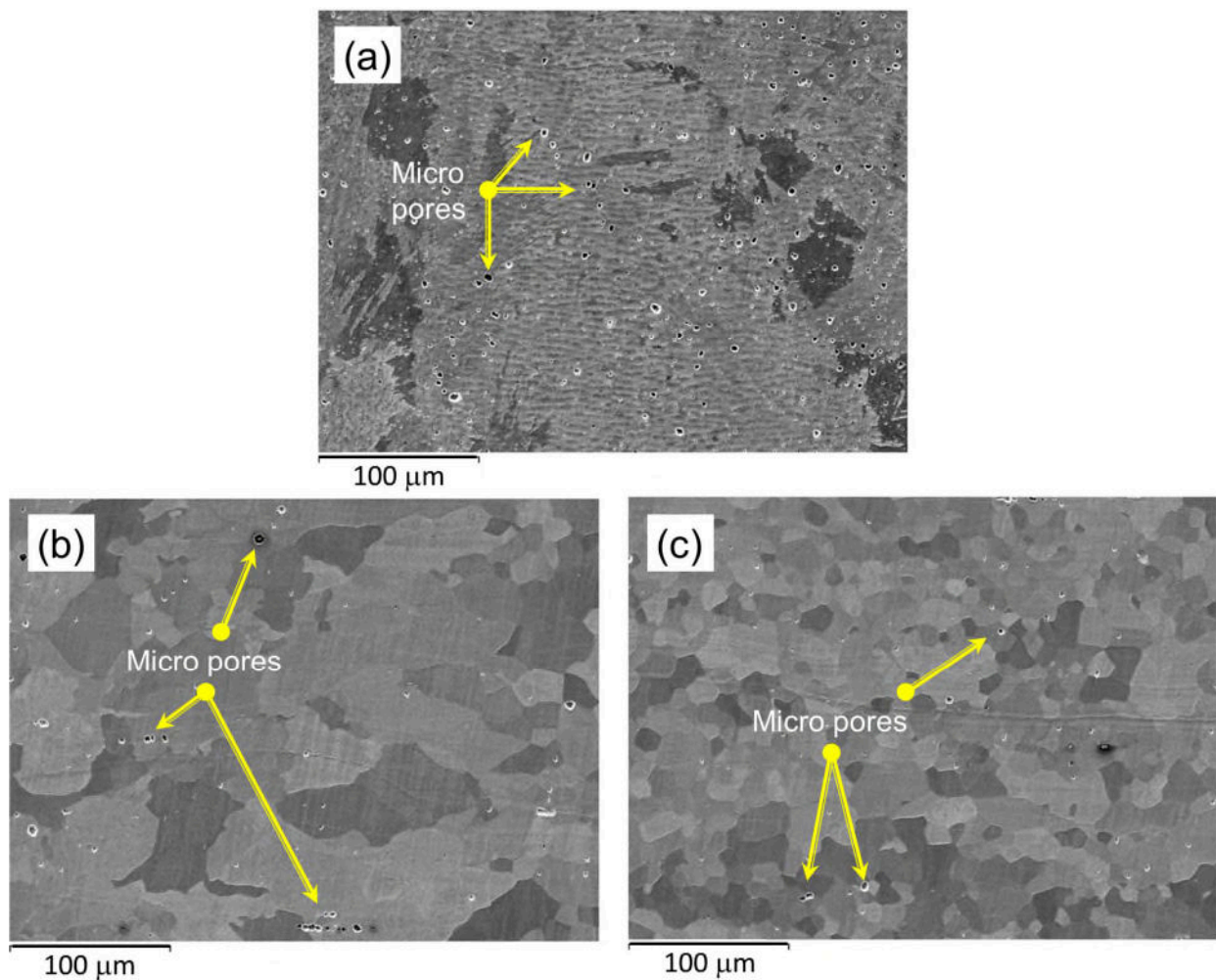


Fig. 6. The tungsten electrode wear in (a) the novel-GTAW torch, (b) the conventional-GTAW torch, and (c) the electrode wear comparison at 20th, 40th, and 80th second.

3.3. Microstructures and microhardness

Fig. 7 shows the microstructures in the three zones of the cross-section of the novel-GTAW sample. It is shown that the heat-affected zone (HAZ) is narrow, with a width of less than 0.28 mm on the top and about 0.4 mm on the bottom. The grain size in the HAZ (Fig. 7b) is much larger than in the base metal zone (BMZ) (Fig. 7c) and the welded metal zone (WMZ) (Fig. 7a). The average grain size in the HAZ is about $60.32 \pm 28.26 \mu\text{m}$, while that value is about $17.25 \pm 3.74 \mu\text{m}$ in the base metal and is very fine (less than $10 \mu\text{m}$) in the weld zone. Few micro-pores were

also observed in all the WMZ, HAZ, and BMZ. This is a typical phenomenon in the welding process of silicon steel because of the influence of the coating layer [25]. However, it was verified by the mechanical testing (Fig. 9) that the micropores do not significantly influence the mechanical properties. **(I-I)** Furthermore, it was indicated in a recent publication that micro-pore is not significantly influenced on the mechanical properties [26]. Therefore, the micro-pore in this paper should not be considered as a main defect. The oxidation layer was observed in the WMZ (Fig. 7a) after the polishing and chemically etching processes. This phenomenon is due silicon elements easily oxidized when the etched samples were exposed in the atmosphere during the capture of metallographic images [9].



(II-8) Fig. 7. Microstructure in (a) WMZ, (b) HAZ, and (c) BMZ.

Fig. 8 shows the microhardness (HV0.5) measured on the three measurement lines corresponding to three locations of the sample (i.e., the top, middle, and bottom locations). The hardness is slightly decreased in the HAZ before increasing in the WMZ. The hardness oscillates from 130 to 155 HV in the BMZ, 130 to 145 HV in the HAZ, and 180 to 193 HV in the WMZ.

These results on microhardness are in line with the microstructures observed in the three regions WMZ, HAZ, and BMZ (Fig. 2) because the microhardness increases with a decrease in the grain size. The HAZ with the coarsest grain size reveals the lowest microhardness. On the other hand, the WMZ with the finest grain size shows the highest hardness.

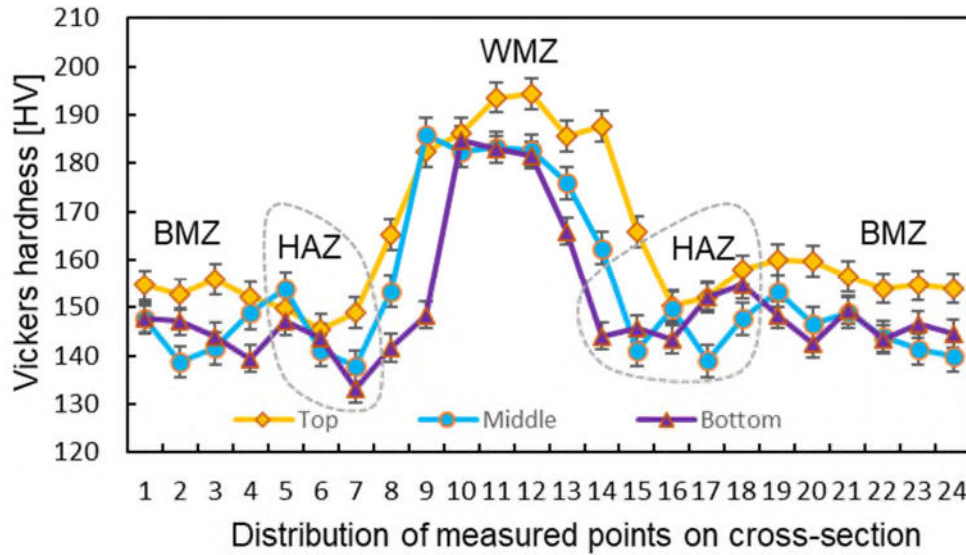


Fig. 8. Vickers hardness distribution.

3.4. Tensile strengths

Fig. 9 presents the tensile test results. All the samples were broken and fractured at positions in the BMZ that are far from the WMZ and HAZ (Fig. 9b). The fractured locations were also almost far from the grips. For all samples, the strength increased until about 430-570 MPa with a very shortly elongated within an initial period of 23 s before they were elongated without increasing the strength. This fracture indicates the ductile failures mechanism [27]. Sample No1 was fractured at 285 s. Other samples (No2 to No5) were elongated over 404 s before the fracture (Fig. 9a). **(III-7)** As shown in Fig. 6, it is revealed that the WMZ was strengthened. Hence, this zone might not yield in the tensile testing. The shrink location was happening in the BMZ after a long plastic deformation (Fig. 9b), while the WMZ and HAZ were still maintained the shape due to the hardening/strengthening during the welding [27]. Therefore, all the tensile samples were broken in the BMZ.

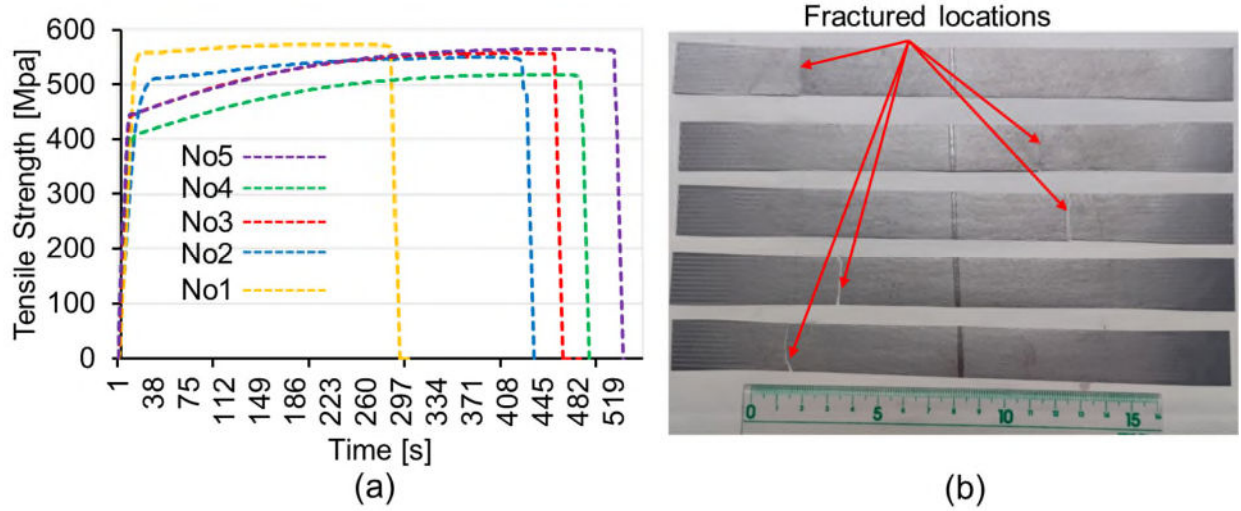


Fig. 9. Tensile test results.

4. Discussion

In conventional welding processes using a tungsten electrode, the arc stability and the arc plasma discharge strongly depend on the conduction between the anode (i.e., the substrate) and the cathode (i.e., the electrode) [28]. In the welding of silicon steel sheets, due to the presence of the non-conductivity and insulation coating layer, the maintenance of the arc plasma discharge and the arc stability becomes much more challenging. At the discharge time of the arc, if the coating layer is not removed, it is extremely difficult to start the arc and begin the welding operation. Moreover, the melted coating layer will cover the molten pool surface, causing the discontinuous conduction during the welding process. The vapor of the coating layer also encloses the electrode, leading to a rapid burn and wear of the electrode (Fig. 5b) and a sharp change of the arc length. Therefore, the arc becomes unstable, and the welding operation is rapidly stopped (Fig. 3 and 5). Therefore, it can be considered that the conventional-GTAW process is not suitable to butt weld silicon steel sheets.

On the other hand, in the novel-GTAW process, the shielding gas supplied to the torch is devised into the two parts. A considerable amount of this gas is blown outside the novel collet and inside the conventional nozzle (Fig. 1b), like the shielding gas in the conventional-GTAW process. Another amount of the gas (called the inner gas) is passed through the holes of the novel collet, creating a higher-pressure gas flow at the outlets of the holes. The inner gas with high pressure can reduce the plasma temperature outside and increase the temperature at the center of the arc-plasma column, making the arc more constricted (Fig. 10a) compared to that in the conventional-GTAW process (Fig. 10b). This phenomenon is called the thermal pinch effect [29–33]. This effect is also observed when evaluating the properties of TIG-welding arcs in CO₂, helium, and argon [31–33]. For example, the presence of CO₂ gas leads to a higher volume enthalpy and a remarkable

reduction in the cross-section of the arc when compared to the TIG argon arc. Thus, the TIG CO₂ arc is much more constricted compared to the TIG argon arc [31–33]. In the current work, the thermal pinch effect makes the weld beads with a narrower bead width on the top side and a larger bead width on the bottom side (Fig. 3, 4 and 5).

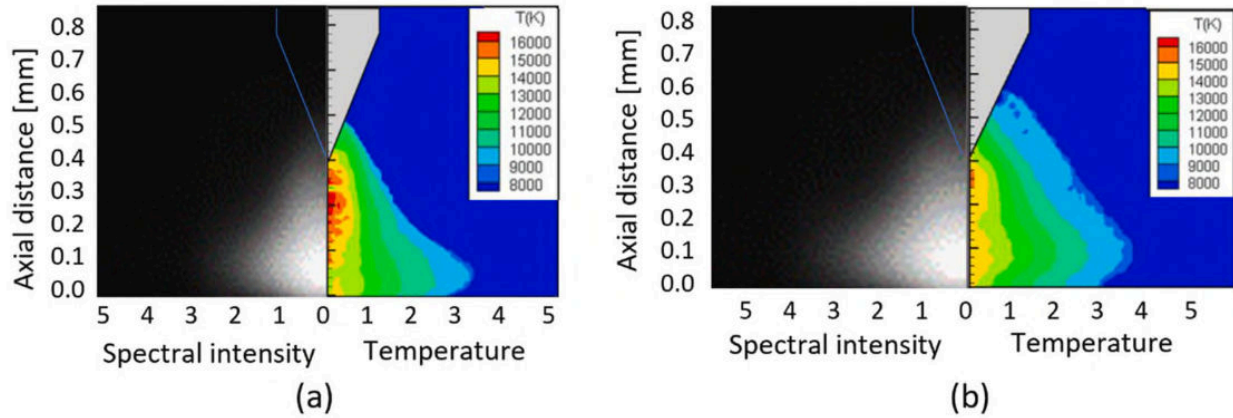


Fig. 10. Comparison of the temperature distribution of the arc between (a) the novel-GTAW and (b) the conventional-GTAW processes [4].

Moreover, due to the high flow rate and velocity of the inner gas, the evaporated metal and coating layer from the melt pool surface can be blown and pushed from the center to the edge of melting pool. (II-11) The pressure and velocity of the arc plasma column in the novel-GTAW process (Fig. 11a) is also increased compared to the conventional-GTAW process (Fig. 11b) [34,35]. As a result, the structure of the evaporated coating layer can be broken down and then blown away from the center to the side and rear of the melting pool. Meanwhile, this characteristic was not established in the conventional-GTAW process. This difference can be clearly seen in Fig. 13. In Fig. 12a (for novel-GTAW case), the evaporated metal from the melting pool and coating layer is blown away from the melting pool center. Meanwhile, it tends to come back and attach to the tungsten electrode in the conventional-GTAW process (Fig. 12b). That is why the electrode tip is still clean after a long time of welding in the case of the novel-GTAW process (Fig. 6), and the weld bead was stably maintained, as shown in Fig. 5. On the other hand, the welding process was quickly failed in the conventional-GTAW process after 80 s of welding (Fig. 5). This indicates that, in the novel-GTAW process, the arc is stable, the arc length is maintained, and the heat input is unchanged. In other words, the welding operation was stable for a long time in the novel-GTAW process.

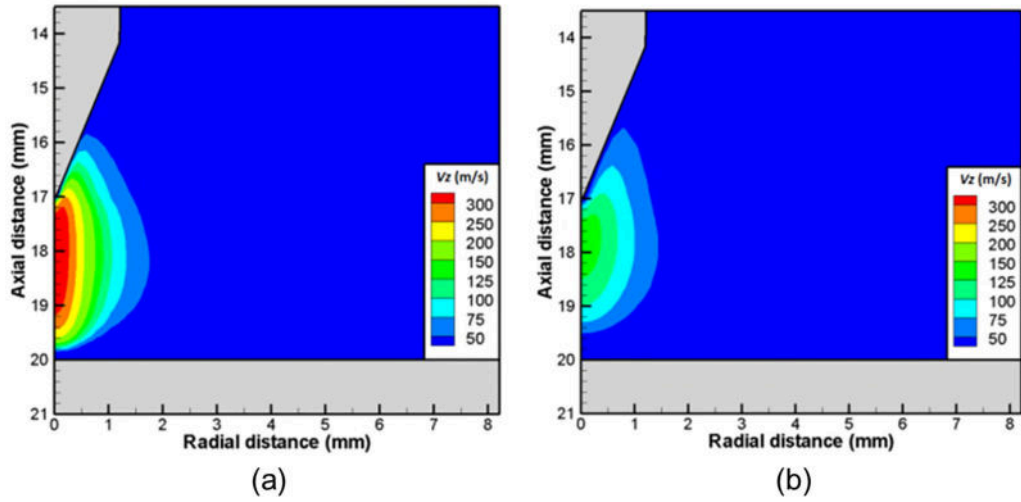


Fig. 11. The velocity distribution of arc plasma column in (a) the novel- and (b) conventional-GTAW processes [34,35].

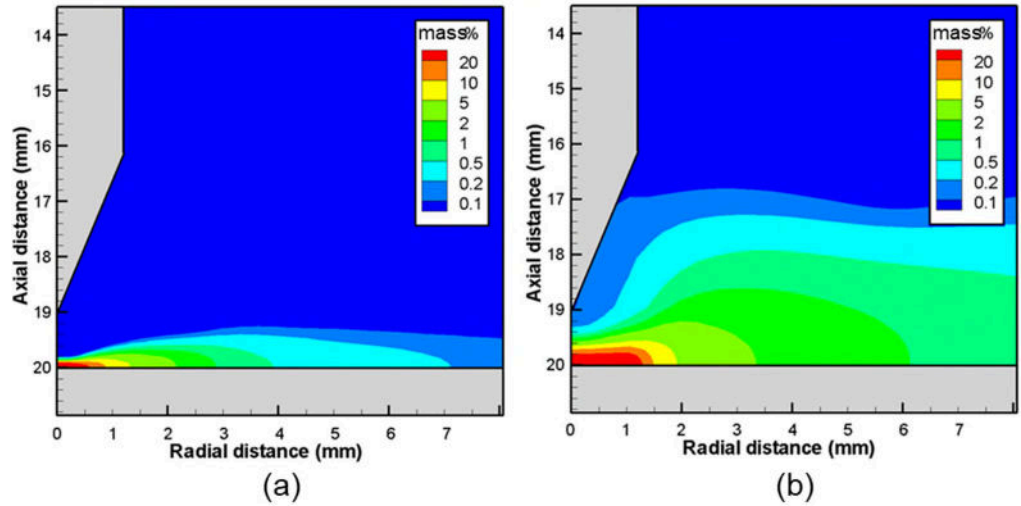


Fig. 12. The distribution of metal vapor in (a) the novel- and (b) conventional-GTAW processes [34,35].

Additionally, the combination of the inner and outer gases enables blowing away the insulation layer and preventing it comes back into the melting pool. Thus, no welding defects (such as undercut and cracks) were observed on the novel-GTAW samples (Fig. 3 and Fig. 4). The surface of the novel-GTAW sample was also cleaner and smoother than that obtained by the conventional-GTAW process. With the efficiency of the novel torch, the bead profile in the novel-GTAW process is much different compared to that in the conventional-GTAW process. The top width of the novel-GTAW weld bead was decreased, while its bottom width was increased when compared to that in the conventional process (Fig. 4). This result is related to the plasma arc pressure and velocity under the influence of the novel collet, as aforementioned. In terms of microstructure, the grain size was about 60 μm in the HAZ and less than 10 μm in the WMZ (Fig.

7), while the grain size in the HAZ and weld zone produced by the conventional-GTAW was about 150 μm and 30 μm , respectively [36]. This reduction in grain size is due to the low heat input and high cooling rate in the novel-GTAW process. **(II-10)** In the novel-GTAW system, in addition to the novel-GTAW torch, a special fixture system (a copper plate and a copper block located upper and under the base metal sheets, respectively) were used for the rapid cooling purpose and to reduce the heat input. The gap (groove) of the copper plate and the copper block increases the cooling rate and efficiently controls the heat input. The energy from the arc plasma is transferred to the copper block, the copper plates, and the substrate, simultaneously. A large amount of the energy is sunk in the fixtures (copper plates and copper blocks) rather than to supply to the melt pool. As a result, a more considerable amount of heat input goes into the base metal. Consequently, this can increase the cooling rate and reduce the heat input. In summary, the novel-GTAW system with the discussed characteristics enables successfully but joining the ultra-thin silicon steel sheets with high qualities.

5. Conclusions

In this study, for the first time, the butt joint of silicon steel sheets with 0.2 mm in thickness was performed successfully by the novel-GTAW process. The results show that the weld beads fabricated by the novel-GTAW process are straight, stable, and without defects. They have a narrower width on the top and a larger width on the bottom side compared to the conventional-GTAW process. The mechanical properties of the welding joints also overmatch that of the base metal, confirming good qualities of the weldment. This success of the novel GTAW process is because of its unique performance characteristics:

(i) The insulation coating layer of the silicon steel sheet surface is effectively removed and blown away during the welding process. Consequently, improving the arc plasma stability capability and thermal pinch effect maintains stable welding operations. The weld bead's appearance is stable without defects, the electrode wear is remarkably reduced, and the mechanical properties of the welding joints overmatch that of the workpiece.

(I-3) (ii) The novel GTAW process superiorly reduces the heat input and increases the cooling rate, ensuring the stable welding and high quality of the ultra-thin sheets due to the combination of a novel-torch with double shielding layer (novel collet) and a special fixture system (copper plate and copper block).

(I-3) (iii) As the electrical material with very high silicon content, it is very sensitive to the oxidation process during welding. However, the novel GTAW process strongly increases the shielding efficiency of the melting pool with a double shielding layer. As a result, no oxidation of the melting pool can be formed, thus avoiding the welding defects. This ensures the quality of the

welded joint.

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