Article

A Study on Vertical Upward Welding of Dissimilar Material and Thickness of Thin Plates Using Novel TIG Welding Process

Ngo Huu Manh[1], Nguyen Van Anh[2,4,*], Murata Akihisa[2], Hideno Terasaki[3]

[1] Sao do University, Vietnam
[2] Murata Welding Laboratories Co., Ltd, Japan
[3] Kumamoto University, Japan
[4] Hanoi University of Science and Technology, Hanoi, Vietnam
* Corresponding author: Nguyen Van Anh ann@mwl.co.jp

Abstract: A study about influence of heat input on welding defects in vertical upward welding position for dissimilar material and thickness using a new variation of TIG welding torch is done with support of advanced inspection methods SEM and EBSD. With vertical upward welding position, control heat input plays an important role to keep the weld stabilization without defects. On the other hand, TIG welding process using a conventional TIG torch (conventional TIG welding process) has low efficiency and it is difficult to control heat input with high accuracy. So, it is considered that using conventional TIG torch is still a challenge for welding thin plates. In this case, a new variation of TIG torch has been developed. This torch used a constricted nozzle to improve plasma arc characteristics. As a result, it can control efficiently the heat input to prevent the excessive or insufficiency for joining thin sheets. For evaluation of welding quality, advanced examination methods SEM and EBSD were applied to directly observe the welding defects. From the results, the formation mechanism of blowhole inside weld zone in case of welding dissimilar material and thickness was discussed. It is pointed out that when sufficient welding current, the change from weld zone to base metal is uniform, no welding defects such as blowhole was seen. However, in case of low welding current, the thinner base metal is insufficient fusion and the change between weld zone and base metal is not uniform. The blowhole was observed at SS400 material side.

Keywords: welding thin sheets; constricted nozzle; TIG welding; EBSD; blowhole; heat input

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1. Introduction

In vertical welding position, both downward position and upward position are being applied in industrial fields [1,2]. With this welding position, the weld pool is strongly affected by gravity. In case of upward position, the direction of gravity force is opposite to with welding direction, meanwhile they are same the direction in case of downward position. In the case of vertical upward welding, the molten metal tends to drop because gravity force is in the opposite direction to the welding direction. For these reasons, welding parameters such as welding current and welding speed are necessary to control strictly for gaining a sound welding quality [3]. Because of difficulties related the influence of gravity force, vertical welding position is considered to be less suitable for thin plates.

In vertical upward welding, the melting material of weld pool is tended in downward direction according to gravity force direction. Therefore, the heat input is increased resulting a large and long weld pool. In this case, the molten metal of weld pool is easy to drop. So, adjustment of welding parameters is strictly requested to prevent this phenomenon. On the other hand, the stainless steel is easily distorted by thermal process, especially in welding thin plates [4,5]. As a result, welding thin plates of stainless steel in vertical upward welding position is easy to be overheat input, resulting in welding defects such as burn-through. Furthermore, in case of welding dissimilar material with

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different thickness, control appropriately heat input for: (1) thinner plate is not excess heat input but (2) thicker plate can be sufficient heat to create a sound joint, it become a complex issue. In order to prevent burn-through, it is necessary to control the penetration through welding parameters such as: reducing the welding current, or increasing the welding speed, etc. [6]. However, decrease the welding current or increase the welding speed, it may result in other defects such as blowhole, lack of fusion, under cut or incomplete penetration due to insufficient heat input. Furthermore, TIG welding process using a conventional TIG torch has low efficiency and it is difficult to control heat input with high accuracy. Therefore, it is considered that TIG welding process using a conventional TIG torch for joining thin sheets is still a challenge.

In order to solve these problems, in recent years, a new variation of TIG torch using a constricted nozzle has been developed by our group for joining super thin plates [7,8]. This torch can improve the plasma arc characteristics and precisely control of the heat input to maintain the welding stability. In this case, the arc column is constricted through the thermal pinch effect to increase the temperature at the center area of plasma [9]. Consequently, in comparison with TIG welding process using conventional TIG torch, better welding quality can be obtained at a high speed and a low current.

In order to obtain good characteristics mentioned above, a novel torch having two nozzles has been developed.

One of them is with a small diameter covering surrounding zone of the tungsten electrode. A small amount of shielding gas from torch is flowed between tungsten electrode and this nozzle with a very high speed. We called this nozzle as “constricted nozzle” and this shielding gas as inner gas. In this case, the inner gas flow played a main role in pressing the plasma column resulting in a more rigidified plasma column in comparison to conventional TIG welding process. Therefore, it leads a concentrated plasma flow with a high-speed plasma jet and high arc pressure impinging on the base metal surface. Another advantage of this gas flow that it increases cooling speed and decreases the temperature of tungsten electrode, therefore cycle life of tungsten electrode can be extended and the stabilization of plasma arc can be kept during a long time.

Another kind of nozzle has similar diameter with nozzle of conventional TIG welding torch. This nozzle is with a large diameter to orient the shielding gas flow far from electrode. We called this nozzle as outer nozzle and shielding gas was controlled by this nozzle as outer gas.

Among the shielding gases, the outer gas has a task as the shielding gas flow in the case of conventional TIG welding process. On the other hand, the inner gas flow causing by narrowing nozzle is concentrated with a high speed in a small gap between tungsten electrode and this nozzle. As a result, double shielding gas is flowed, thereby preventing the reduction of the shielding effect which has been a problem in the conventional TIG welding process. In addition, due to using narrowing nozzle, it accelerated the plasma jet through a high-speed inner gas flow as mentioned above. Therefore, (1) the magnetic field acting on the arc is strengthened; (2) the energy density of the arc is enhanced and the arc column is rigidified; (3) discharge capacity of electrons in plasma arc is increased strongly in comparison to TIG welding process using conventional TIG torch [10]. In addition, due to the high-speed inner gas flow, the metal evaporation from weld pool is pushed outside to prevent the attachment of evaporated metal on the tip of tungsten electrode. Consequently, the tungsten electrode become more cleaning, reduce contamination and the arc length can be set up in extremely short distances. This is a useful characteristic in order to prevent the expansion of the plasma column, in which this advantaged point did not have in conventional TIG welding process. From all of above welding with high speed and low current can be obtained.

Recently, our group was been starting to study the mechanism of this welding technology. In a paper of Konishi et al., the influence of constricted nozzle was discussed using numerical simulation in case of 3 mm arc length [11]. The results showed that in comparison to conventional TIG welding process, the heat flux on anode surface was increased. Especially at the center of arc, heat flux was highly increased.

However, the simulation is limited by boundary conditions and assumptions. Therefore, it is difficult to obtain comprehensive and full understanding about the mechanism of this process with only numerical method. Therefore, the experiment is also indispensable. In a recent research, Miki et

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al. discussed the influence of oxygen contamination and heat input on the anode surface in order to ensure a high-quality welding [12]. The experimental results evidenced that in case of TIG welding with a constricted nozzle, the oxygen content on weld pool surface is lower in comparison to conventional TIG welding process. In another paper, Anh et al., did the experiments in practical welding conditions of the industrial factories. This paper indicated that super thin sheets 0.1 mm can be welded with sound quality at an extremely short distance of arc length (0.1 mm), high welding speed and low welding current with no surface defects such as undercut and burn-through [13].

However, there are no reports related to welding quality and welding defects inside weld zone of this process. Furthermore, welding defects is always a huge challenge because it can cause the serious damages [14]. Therefore, this paper tried to observe the welding defects in case of butt-welding thin sheets (0.2 mm and 0.4 mm). Furthermore, in welding thin sheets, welding defects inside weld zone are difficult to examine by conventional methods due to insufficient resolution of equipment in an extremely narrow region. Therefore, this paper has utilized advanced inspection methods SEM and EBSD to directly observe welding defects.

2. Experimental method

2.1. Welding condition

In this experiment, two kinds of butt joints were done including: (1) butt-joint of two of the same material and (2) butt-joint of dissimilar material and different thickness. The materials are SS400 with thickness 0.2 mm and SUS430 with thickness 0.2 and 0.4 mm. Table. 1 showed the welding conditions and base materials.

Table 1. Base materials and welding conditions.

No.	Thickness (material) [mm]	Welding current [A]	Welding speed [mm/min]	Arc length [mm]
No.1	0.2 (SS400)-0.2 (SS400)	22	3000	0.3
No.2	0.4 (SUS430)-0.4 (SUS430)	55	3000	0.3
No.3	0.2 (SS400)-0.4 (SUS430)	55	3000	0.3
No.4	0.2 (SS400)-0.4 (SUS430)	65	3000	0.3

2.2. Experimental equipment

A schematic illustration of experimental set-up is shown in Fig. 1. Main equipment for this experiment was a welding power source MFW-400FTV from Murata Welding Laboratories Co., Ltd. The tungsten electrode with diameter of 1.6 mm was utilized. The tip angle was fixed at 30 degrees. The distance between tungsten electrode tips with workpiece surface (arc length) was set up at 0.3 mm. Welding speed was 3000 $mmmin^{-1}$. The inner gas and outer shielding gas were pure Ar. The flow rate of inner gas was 2.5 $lmin^{-1}$. The flow rate of outer gas was 5.0 $lmin^{-1}$. The welding current was changed in three levels: 22 A; 55 A and 65 A.

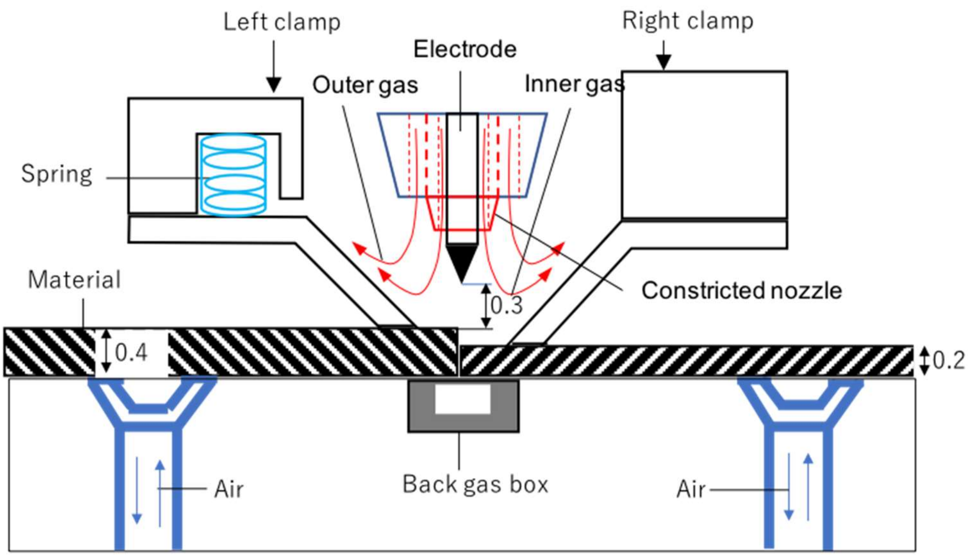

Figure 1. A Schematic illustration of constricted nozzle TIG welding process.

3. Experimental results

Fig. 2 indicated the weld bead appearance in all cases. It can be seen that weld pool seems be extended in downward direction due to the opposition of gravity force and welding direction. As a result, it can be seen that the weld pool boundary looks like the continuous semi-circle in downward direction in all cases. No cracking occurred in the weld zone under all welding conditions from No.1~No.4. Moreover, the beautiful weld bead was formed in cases of welding between SS400 materials each other (No.1) or between SUS430 materials each other (No.2). In welding dissimilar materials between SS400 and SUS430 (No.3 and No.4), the weld bead of SUS430 side is more beautiful than the bead of SS400 side.

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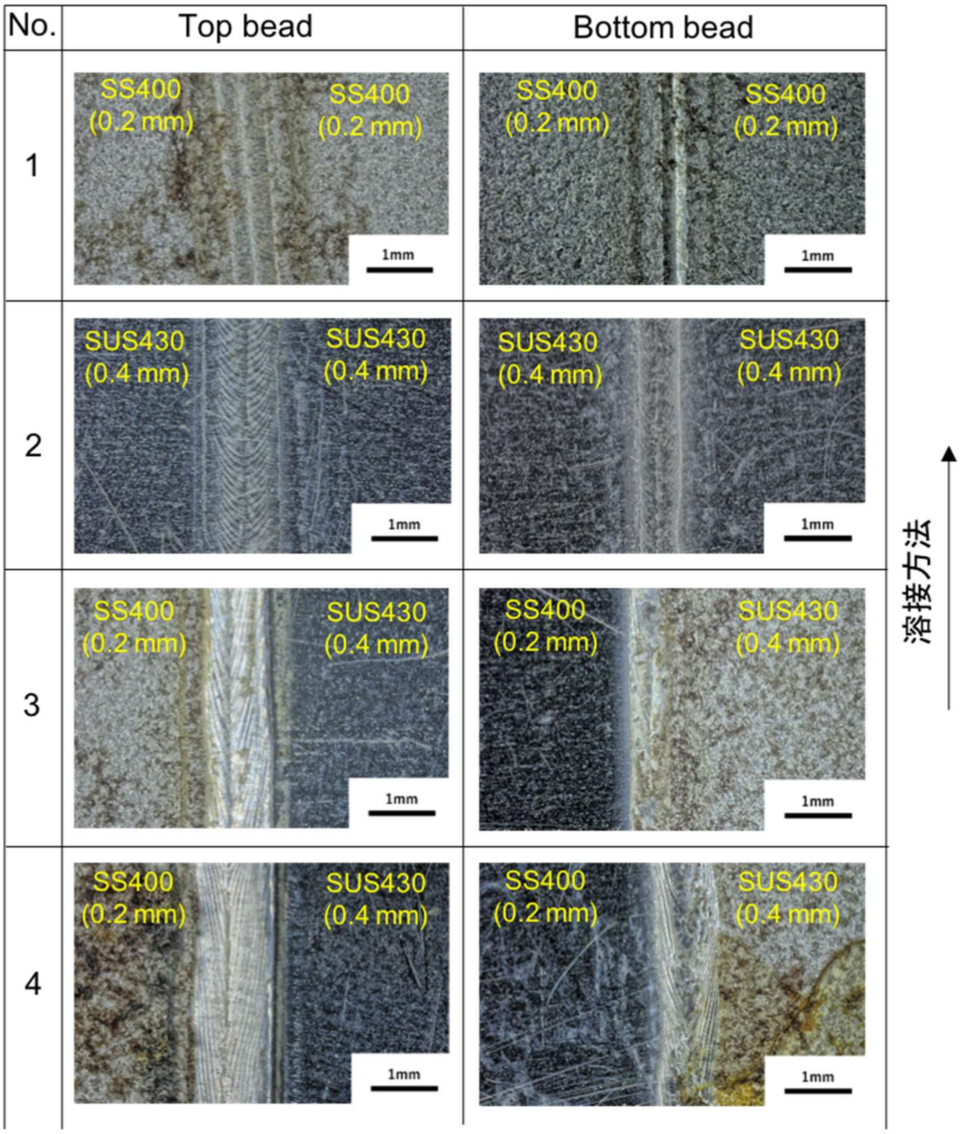

Figure 2. Weld bead appearance.

Fig. 3 presented the EBSD analysis results in weld zone of welding between SS400 materials each other (No.1 case). In here (a) is IQ map, (b) is grain map, and (c) is grain size. The red dotted line in Fig.3 (a) indicated the butt position of joint. In case of welding between SS400 each other, no welding defects such as cracking are observed. The grain size is small with distribution within 5~80 micron and average size about 30 micron. A large amount of small size grains within 10~50 micron can be seen.

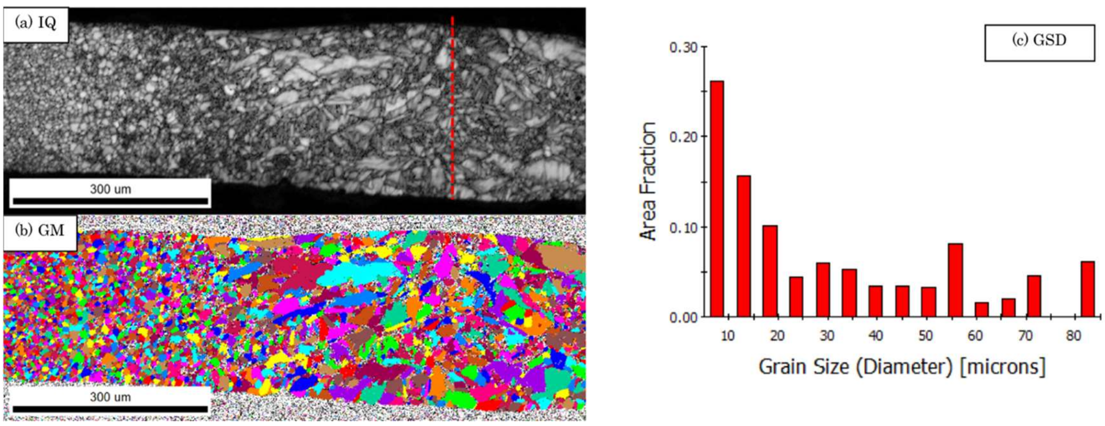

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Figure 3. EBSD analysis results in weld zone of welding SS400 materials each other.

Figure. 4 indicated the SEM observation results of welding between SS400 materials each other (No.1 case) with (a) is base metal, (b) is heat affected zone (HAZ), and (c) is fusion zone. It can be seen that there are no defects in welding between SS400 materials each other.

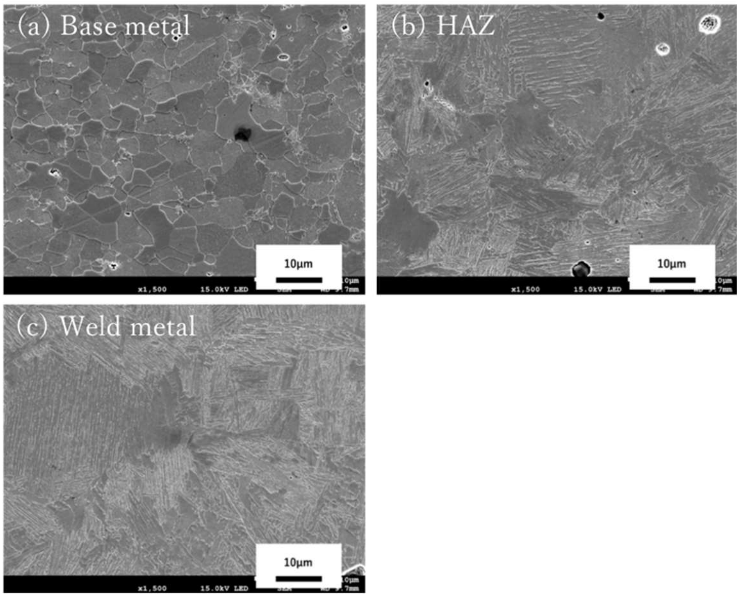

Figure 4. SEM images in weld zone of welding between SS400 materials each other.

Fig. 5 presented the EBSD analysis results in weld zone of welding between SUS430 materials each other (No.2 case) with (a) is IQ map, (b) is grain map, (c) is grain size. The red dotted line in Fig.5 (a) indicated the butt position of joint. No cracking can be observed in this welding condition. However, because SUS430 is a ferritic stainless steel, the grains are coarsened. A large amount of large size grains within 50~140 micron can be seen.

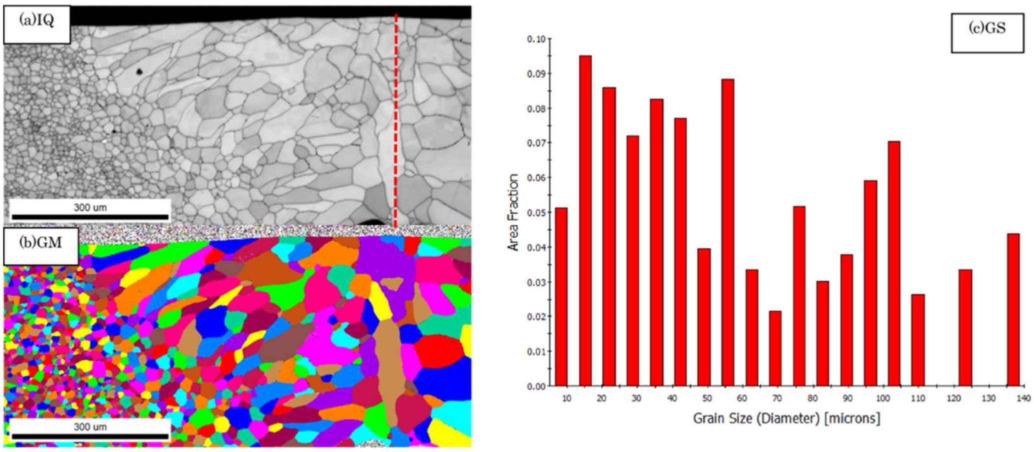

Figure 5. EBSD analysis results in weld zone of welding between SUS430 materials each other (No.2).

Fig. 6 showed the EBSD analysis results of welding the dissimilar material and dissimilar thickness of SS400 (0.2mm) + SUS430 (0.4mm) (No.3 case). The left side is the base material of SUS430. The right side is the base material of SS400. (a) is IQ map, (b) is grain map, (c) is grain size. The red dotted line in Fig.6 (a) indicated the butt position of joint. In this case, circular black shadows can be seen and it is concentrated at the SS400 material side. In addition, it can be seen that the mixture of the materials in the melting zone is not uniform.

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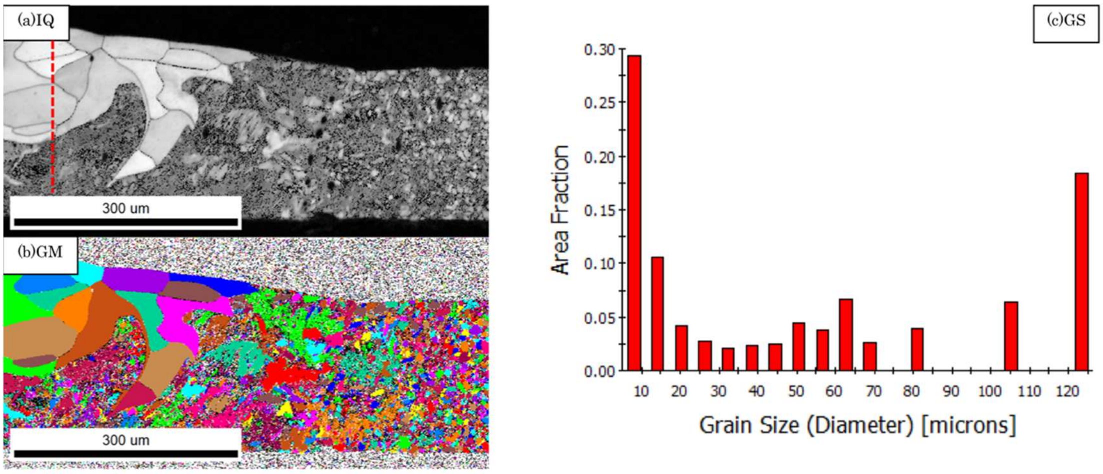

Figure 6. EBSD analysis results in weld zone of welding SS400 +SUS430 (No.3) materials.

Fig. 7 described the EBSD analysis results of welding dissimilar material and thickness of the SS400 (0.2mm) + SUS430 (0.4mm) (No.4 case). The left side is the base material SUS430. The right side is the base material SS400. (a) is IQ map, (b) is grain map, (c) is grain size. The red dotted line in Fig.7 (a) indicated the butt position of joint. In this case, circular black shadows were not observed. Moreover, in melting zone, mixture of the materials is uniform. However, the grain size is larger in comparison to No.3 case.

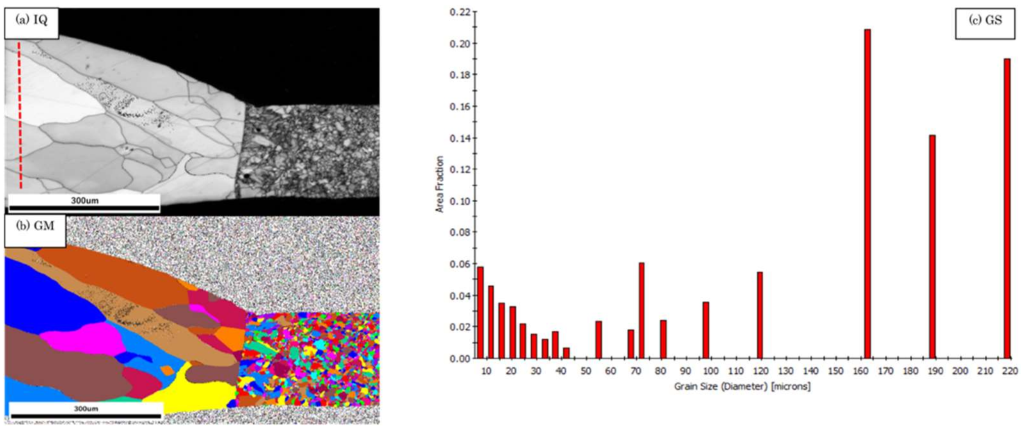

Figure 7. EBSD analysis results in weld zone of welding SS400 +SUS430 (No.4) materials.

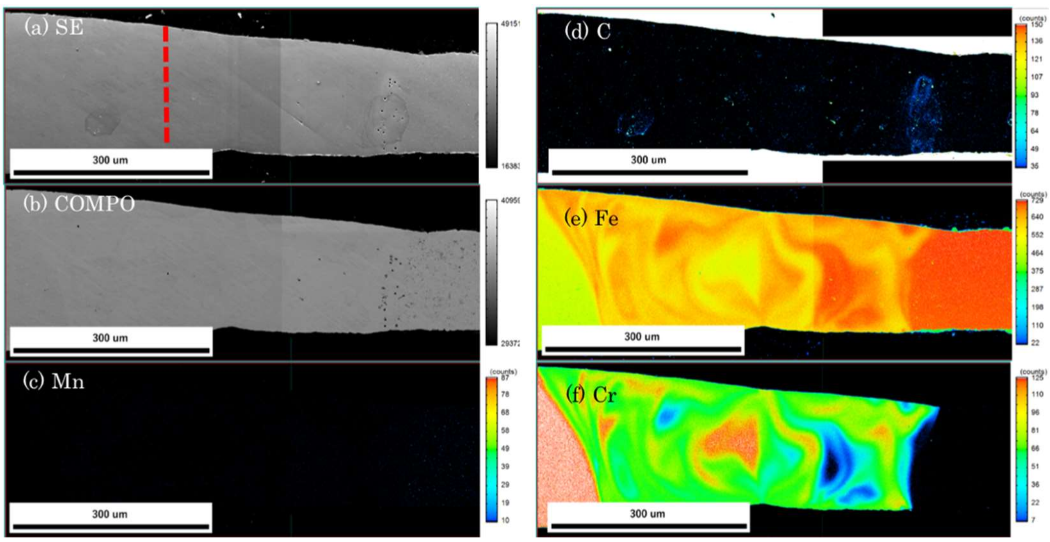

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Figure 8. Elemental analysis results in weld zone of welding SS400 +SUS430 (No.3) materials.

Results of elemental analysis in No.3 case are exhibited in Fig.8. The left side is SUS430 material. The right side is SS400 material. (a) is SE image, (b) is COMPO image, (c) is elemental distribution of Mn, (d) is elemental distribution of C, (e) is elemental distribution of Fe, and (f) is elemental distribution of Cr. The red line in Fig.8 (a) represented the butt position of joint. Fig.8 (c)-(f) indicated that in the red zone the distributed elements is more appeared than to the blue zone. Fig.8 (e) and (f) indicated that the material is not mixed uniformly with very low Fe distribution and the very high Cr distribution at the central region of joint. Also, according to Fig.8 (a), (b), and (d), the black shadow seen in Fig.5 (a) is concentrated outside weld zone on the SS400 base material side.

Fig. 9 showed the results of elemental analysis in case of welding SS400 + SUS430 (No.4 case). The left side is SUS430. The right side is SS 400. (a) is SE image, (b) is COMPO image, (c) is elemental distribution of Mn, (d) is elemental distribution of C, (e) is elemental analysis of Fe, and (f) is elemental distribution of Cr. The red line in Fig.9 (a) represents the butt position of joint. Fig.9 (c)-(f) indicated that the distributed element in the red region is more than in the blue region.

In comparision to Fig.8 (e) and (f), it can be considered that No.4 case has more uniform material mixture than No.3 case. Furthermore, from Fig.8 (a), (b) and (d) no black shadow can be seen.

Fig. 10 presented a magnified photo of the black shadow in No.3 case. As shown in Fig.10 (b) and (c), black shadow, they are in circular and regular wave patterns. Furthermore, from Fig.8 (c)-(f) it can be seen that almost no other elements than Fe was detected at SS400 material side. From these results, this black shadow is considered as a blowhole. From Fig.3, Fig.5, Fig.6, Fig.7, it can be said that blowhole occurred in welding condition of No.3 case. No blowhole was observed in other welding conditions.

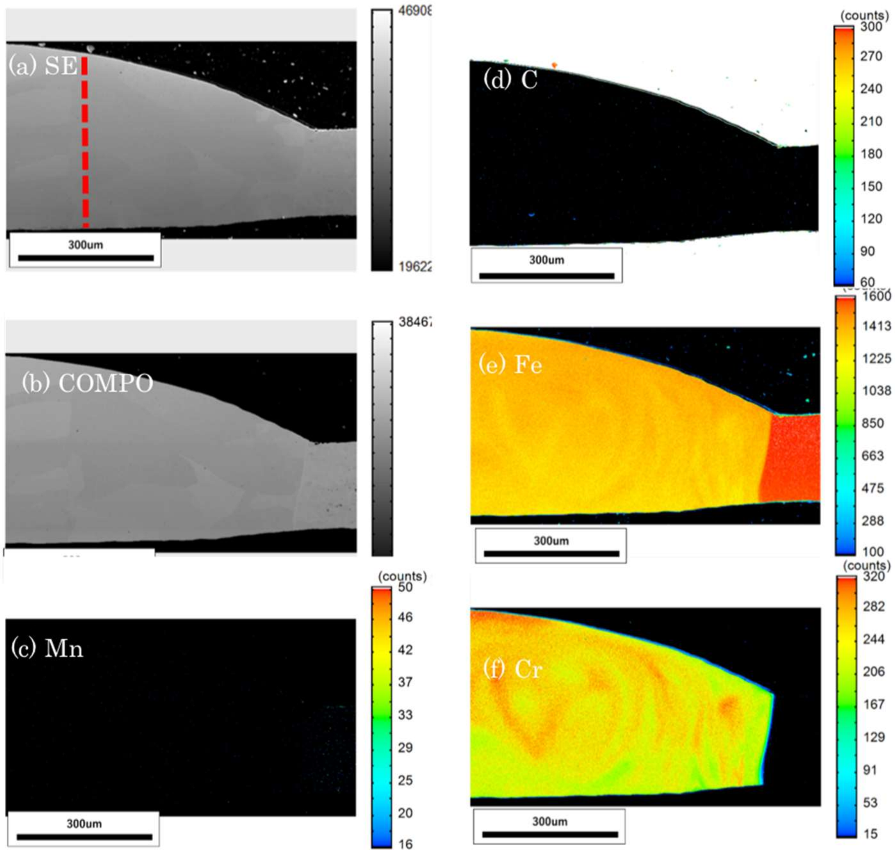

Figure 9. Elemental analysis results in weld zone of welding SS400 +SUS430 (No.4) materials.

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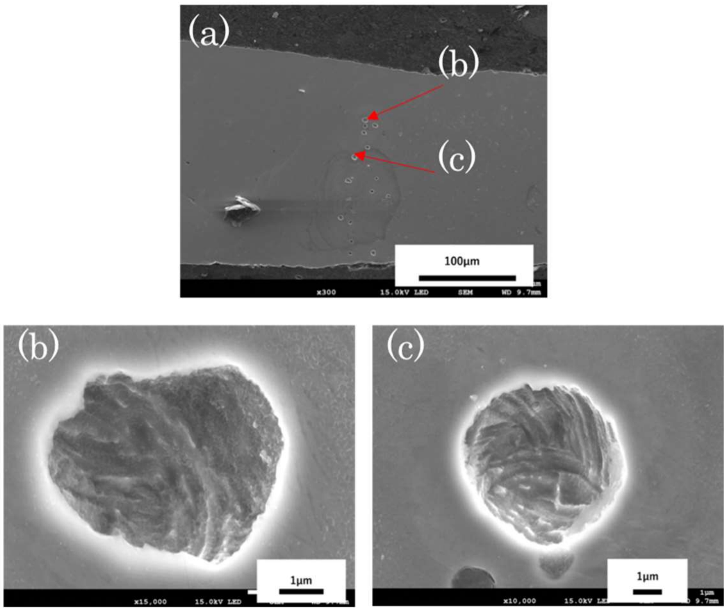

Figure 10. A magnified image of the black shadow.

4. Discussion about welding defect formation

From the results of this paper, it can be considered that butt welding thin plates in vertical upward welding position can be done well by a new variation of TIG welding technology. Weld bead was beautiful. In the butt welding of the same material and the same thickness, no welding defects such as crack or blowhole were found. In case of dissimilar materials and thickness, the welding defects such as blowhole can be occurred with different levels of welding current.

As shown in Fig.3 and 4 (No.1 case), in the case of SS400 stainless steel, the size grains are small. Grain size increased uniformly from base metal toward central zone. No welding defects such as crack or blowhole can be seen. A good uniform between base metal and weld zone can be seen.

As shown in Fig.5 (No.2 case), in the case of SUS430 material-ferritic stainless steel, the size grains are grown much. In this welding condition, welding at a high speed with a suitable current, grain growth can be inhibited. In addition, because of shortening the arc length, the thermal diffusion to the surroundings was prevented, thereby only a narrowing zone in which grain growth was occurred.

From Fig.6 (No.3 case), in case of welding dissimilar metals and different thickness with a low welding current (55 A), it was not uniformly mixed materials. Blowholes appeared and it located at SS400 material side.

From Fig.7 (No.4 case), in case of welding dissimilar metals and different thickness with a higher welding current (65 A), it can be seen that it was uniformly mixed materials. No blowhole or other welding defects can be seen in this welding condition. However, the grain size at SUS430 material side was larger than that in case of No.3.

In cases of No.1 and No.2, it is thought that a suitable welding current was applied. In case of No.2, the grain size in weld zone was much larger than that in base metal. No welding defects can be seen. A sound welding quality can be obtained.

In case of No.3, blowhole was generated due to low welding current. In case of No.4, no blowhole and other welding defects can be seen. This is because the amount of necessary heat for melting is sufficiently obtained due to high welding current (65 A). In this case, the grain size is bigger in comparison to No.3 case. Generally, the grain growth can reduce the joint strength, therefore, it is necessary to control this issue with a suitable welding condition for keeping the joint strength without welding defects.

In welding with condition No.3, blowholes were generated. Generally, it is thought that blowhole is occurred in the entire molten metal due to the low heat input. However, Fig.6, Fig.8 and

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Fig.10 showed that the blowhole is concentrated at only the part of base material SS400. On the other hand, in case of welding the same material and the same thickness, almost no blowholes are seen in condition of No.1 and No.2 even though the current is low (22 A and 55 A). From results above, it is considered that in the case of butt welding of dissimilar material and thickness, blowholes are generated by the mechanism from 1~4 as implicated in Fig. 11. The states in Fig.11 proceed in the order of 1 to 4. First, the base material is melted and then the molten metal is pressed by the plasma flow (see 1). At this time, the plasma flow as shown in 2 with larger amount of heat input is supplied for SUS430 material and smaller amount of heat input is supplied for SS400 material. The heat input makes melting the materials as 3. Finally, all material can be melted as 4. Because the heat input is mainly supplied on SUS430 materials, at SUS430 material side, the heat input is sufficient to procedure a sound bead with no welding defect but the heat input is insufficient at SS400 material size. This caused the blowhole like explanation above. In addition, in case of low welding current (No.1 and No.2), even though low heat input, it is still sufficient heat to ensure a sound welding joint without welding defects These results are based on the efficiency of constricted nozzle TIG torch with the high heat input density as implied above.

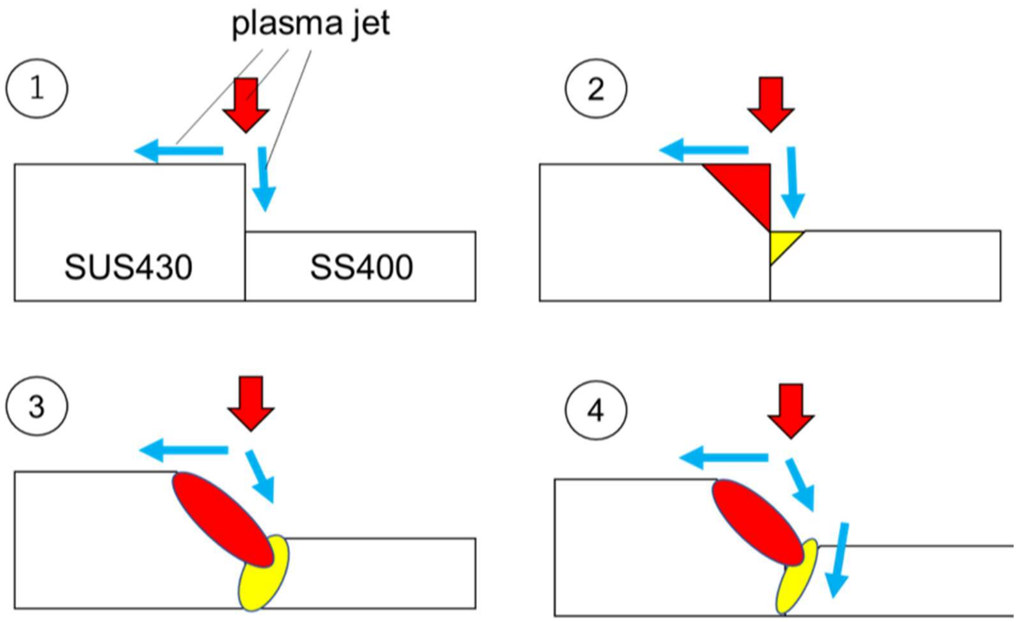

Figure 11. Prediction of blowhole formation mechanism.

As described above, in welding thin plates, insufficiency or excessive of heat input can cause defects, especially for stainless steel. In vertical upward welding case, insufficiency of heat input can cause defects such as blowhole and excessive of heat input can cause burn through. Therefore, it is important to suppress unnecessary heat input by increasing heat input density. As described in" introduction" part, constricted nozzle TIG welding can achieves high heat density and narrow zone of heat input due to an extremely short gap of arc length (in this paper, the arc length was set up at 0.3 mm). In other words, this welding process is able to control unnecessary heat input with high accuracy, so it can apply in welding extremely thin plates for preventing the welding defects.

5. Conclusions

In this paper, a directed observation of welding defects inside weld zone of butt-joint in vertical upward welding position using a constricted nozzle TIG welding process for dissimilar material and thickness was done. Several main conclusions can be drawn:

1. In the case of welding between SS400 material each together (No.1 case), there were no defects such as cracks or blowhole.
2. In the case of welding between SUS430 materials each together (No.2 case), no welding defects

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can be seen.

3. In the case of welding dissimilar materials and different thicknesses, blowholes were generated when the heat input was low (No.3 55 A). At the same time, the mixing of materials was not uniform.
4. By increasing heat input (No.4 65 A), it can weld successfully in suppressing the generation of blowholes. Furthermore, the mixing the materials is uniform. No other welding defects were not found.
5. In addition, in case of low welding current (No.1 and No.2), even though low heat input, it is still sufficient heat to ensure a sound welding joint without welding defects.
6. Unnecessary heat input can be prevented by TIG welding using a constricted nozzle. Using this technology can prevent defects caused by excessive or insufficiency of heat input such as burn-through and blowhole.

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