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THE EVALUATION ON PERFORMANCE OF NARROW-GAP WELDING THICK STEEL PLATES UNDER THE INFLUENCE OF MAIN WELDING PARAMETERS

Vu Duong
School of Engineering and Technology
Duy Tan University
3 Quang Trung str., Da Nang, Vietnam, 550000
duongvuaustralia@gmail.com

Abstract

This work presents the experimental results of narrow gap butt welding of steel plates with large thickness by using the Metal Active Gas (MAG) welding method. The typical defects are accompanied with this process such as the infusion in the side wall and the porosity due to the narrow gap which affect on the melting process. Thus, some publications noted the results of welding for the thickness up to 20–30 mm and the chamfer angle about 30° using GMAW/MIG, GTAW/TIG, SMAW and new development such as laser – arc hybrid, laser multi-pass technique, super-TIG welding etc. But the production requires the solution to save the costs by the reduction of time, labour and investment keeping the standard quality. That is the aim of this study. In order to improve the quality of weld joint and increase the productivity of the process, is it suggested to develop the innovative welding process, in which the welding voltage – U_w, the translational velocity of the tip – V_t, and rotational velocity of the tip – V_r, are changing. This helped to increase the thickness of steel plates up to 50 mm and the chamfer angle decreased at 15°, providing the satisfied quality of the weld. The micrography study serve as the preliminary proof of this hypothesis.

The microstructures in 4 regions, such as the weld center zone, heat-affected zone (HAZ), parent metal region, and the boundary between the weld metal and the HAZ were examined. The microstructures of 13 positions from different experiments are investigated using the optical microscope (Axiovert 25). These experiments covered all specific points (node) locating accordingly to three layers from bottom to top of the weld joint. The findings proved the welding quality is similar in case of narrow gap but the chamfer angle is twice lower and the thickness is increased. The result of the study enhances the productivity due to saving the labour cost and the welding materials. It is recommended to consider the effect of other factors (such as cooling conditions, dwell time when the arc approaching the side walls) to optimize the weld quality. There is the huge volume of the heavy steel constructions with the thick steel construction and specific narrow gap in industry. The results of this study with the optimization and more deeper evaluation the influence of main parameters of welding process to eliminate the typical defects will be the valuable recommendation for the managers and engineers in the production of metallic constructions.

Keywords: narrow gap MAG welding, thick plate welding, microstructure, design of experiment.

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1. Introduction

The effectiveness of the welding process depends on some attributes, such as costs, the production time, and the quality of welding joints. This matter is more vital dealing with the thick plates of steel for special structures in industry. Therefore, the narrow gap welding has been widely used in ships, construction, nuclear and fossil fuel industries, etc. [1]. Thus, the Japanese inventor developed the new method for narrow gap welding, using a welding wire containing a small amount of rare earth element to stabilizer the arc in mode of direct current electrode negative. But up to the present, this technique is used only for the welding 25° single bevel groove. There is the lack of any analysis of the experiment data to verify the development. A new rotating-tungsten narrow-groove technique was applied in [2] demonstrated the rotation of the tungsten tip, leading to the periodical changing of the distance between the welding tip and the sidewalls. This novelty helped to solve the problem of infusion in narrow gap welding. Nevertheless, the thickness of the alloy steel is only up to 16–20 mm and the value of the rotation of the welding tip was not mentioned. To conduct the narrow gap welding of mild steel with the thickness up to 40 mm, the groove width is at the range of 8–10 mm, has been suggested the new method: laser – arc hybrid welding process [3]. But the mechanical properties of the welding joint is not stable according to the height, namely at the bottom part the weld had the lowest tensile strength. The production cost is the problem due to the complex of the welding equipment and the requirement of the high skill labour. The research team in [4] reported their promising technology for welding thick-walled component made of the high alloy in modern power plants based on the laser multi- pass technique. The wall thickness in their experiment is of 72.5 mm. The limitation of this technique is the precondition in design and test the suitable welding expensive equipment to meet the specific specifications. The rotation of the welding tip in narrow gap welding technique was mentioned also in work [5], but the shielding gas is the mix: 20 % CO_2+Ar. As a short report, the authors did not provided the data for validation their recommendations. In order to increase the productivity in semi- narrow gap welding, the innovative solution was presented in [6] where the super -TIG welding using C-type strip as the filler metal. The chamfer angle is 15°, but the root gap was 10 mm and the thickness of steel plates is up to only 20 mm. In [7], it is announced a successful building of a quality prediction model for narrow gap MAG welding for Q235 steel plates with a groove height of 20 mm. It will be better for the recommendation in industry if this model was verified by the experiment since the simplicity of the MAG process. In [8], it was applied a narrow gap welding to join steel plates with a thickness of 31.75 mm of combat vehicles. The difference in this study is the specific design of the X-groove weldment. The specific military standards MIL-HDBK-1941 and MIL-STD-12560 require the multi-pass welding technique. Authors of [9] presented some preliminary research results on both theory and practice of butt welding of steel plates with narrow gaps. They used the steel specimens having a small thickness (up to 20 mm) and large chamfer angle ($\alpha = 30°$ chamfered side). However there is limited research assessing the weld quality of extremely thick plate butt welding (up to 50 mm or more) with narrow gaps and small chamfer angles ($\alpha = 15°$ on each side). There were some publications investigating the influence of wire-electrode rotation speed, longitudinal magnetic field and the oscillating arc on the fusion of sidewalls for narrow groove weld [10–12]. For example, in [10], the authors focused on the effect of the rotation technique, which encourages a free flight metal transfer mode at lower welding current than the original transition current. Finally the wire-electrode rotation interferes in the melting efficiency of the wire. The results obtained by the oscillographic technique. Since the oscillation arc contributes the significant influence on the efficiency melting in narrow gap welding, it is suggested to apply the extra alternating longitudinal magnetic field to avoid the welding defects such as the infusion at the side walls. However, the absence of the groove design parameters in the experiment limited its application in the production [11]. The sophisticated method in [12] is used for vertical narrow gap welding. The influence of the bending angle and groove gap on the efficiency of the fusion was investigated. The macrophotography technique helps to explain the morphology of the welding pool. It is needed the further study in terms of the experiment design in wide range of changing parameter, especially including the influence of translational speed of welding.

From the above mentioned analysis, the aim of this work is the new process focusing on the main parameters such as the welding voltage – U_w, the translational velocity of the tip – V_t, and rotational velocity of the tip – V_r and the evaluation their influence in welding workpieces with thickness up to 50 mm, small chamfer angle of 15°, and narrow gaps of 10 mm, using the MAG welding with the shielding gas 100 % CO_2. In addition, typical defects occurring in the weld are also presented. The experimental results with simultaneous change of main welding parameters will also provide valuable information of the influence of bevel angle on the welding quality.

2. Materials and method

Object of research: the performance of butt weld of workpieces with thickness up to 50 mm, small chamfer angle of 15°, and narrow gaps of 10 mm, using the PLEXTEC® 500x welding machine and MG70S-6 welding wire. The welding tests are conducted under 100 % CO_2 shielding gas. The range of variation of main parameters is as follow: the welding voltage $U_w = 22÷30$ V; the translational velocity of the tip $V_t = 4÷8$ m/h; and the rotational velocity of the tip $V_r = 18÷30$ rpm.

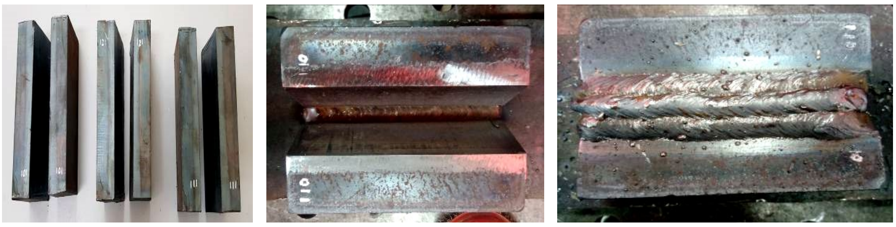
The main hypothesis of the study is the positive influence of suggested welding process on the satisfied quality of weld joint basing on the micrography analysis of samples in 4 main zones: central, boundary, heat affected and parents metal. For more details, the investigation was conducted in 3 layer: bottom, middle and top according to the height of the weld.

Assumptions made in the work such as above mentioned: the range of the experiments covers the optimum zone to achieve good quality of weld.

For the simplifications in the work it is suggested to conduct 13 experiments instead of 27 experiments according to the full design experiment. The final analysis of the results will decide if need to conduct the full design experiment.

The design of experiment for 3 process parameters (the welding voltage – U_w, the translational velocity of the tip – V_t, and rotational velocity of the tip – V_r) and 3 levels was performed. In the previous experiments, the plan of 27 experiments was conducted to study on characteristics of narrow gap butt joints with chamfered edges using MAG welding method.

The sample material used in the experimental welding is SS400 steel [13]. The length, width, and thickness of the workpiece are 250, 120, and 50 mm, respectively. The chamfer angle, which is formed by the vertical plane and sidewall of the specimen, is chosen as 15° on each side. **Fig. 1** shows the workpieces prepared for the welding test and the sample after welding.



a *b* *c*

Fig. 1. Butt welding of thick steel plate with narrow clearance: *a* − workpieces with small chamfer (α = 15°); *b* − fixing workpieces with gap spacing equal to the torch tip diameter; *c* − finished welding sample

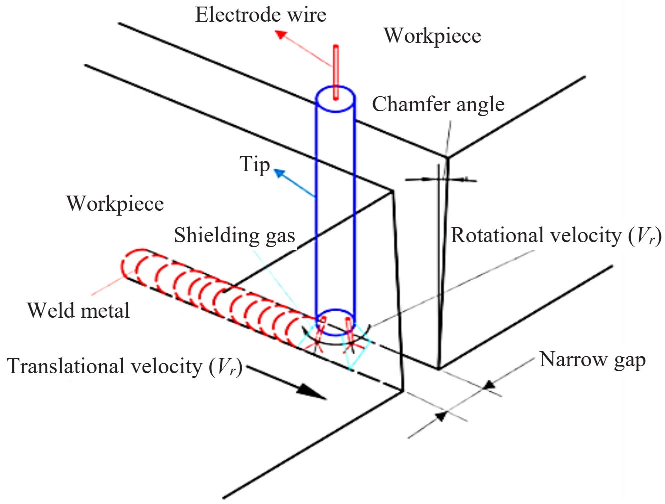
A PLEXTEC® 500x (The Lincoln Electric Company, USA) welding machine [14] was used for the experiments, as shown in **Fig. 2**. The MG70S-6 electrode wire diameter is 1.2 mm [15]. And all the welding tests are conducted under 100 % CO_2 shielding gas condition [16, 17].

Fig. 2. PLEXTEC® 500x welding machine and welding process parameters

Fig. 3, *a* shows the schematic diagram of the MAG welding. The welding tip rotates and simultaneously moves along the gap during welding. **Fig. 3, *b*** shows the specimen and welding tip in the gap during welding. **Fig. 3, *c*** and **Fig. 3, *d*** illustrate the specimen after welding several layers.

The experiment plan is based on the design of the experiment for 3 process parameters and 3 levels. As a result, total 27 experiments are carried out [9]. Three process parameters include: the welding voltage U_w = 22÷30 V; the translational velocity of the tip V_t = 4÷8 m/h; and the rotational velocity of the tip V_r = 18÷30 rpm.

Fig. 4 shows the optical microscope (Axiovert 25) [18], which is used to monitor the microstructure of the butt-welded joints.



a

b

c

d

Fig. 3. Experiment of MAG welding for butt joints of thick plate with narrow gap: *a* – welding diagram; *b* – the welding tip in the gap during welding; *c* – specimen at a time when several completed layers; *d* – surface of a welded layer.

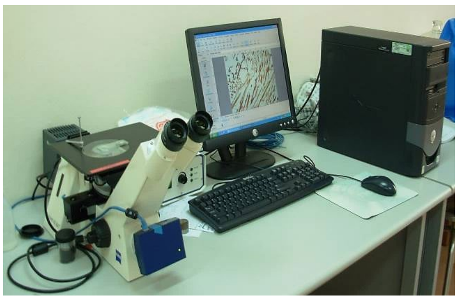


Fig. 4. The optical microscope used for monitoring the weld joint microstructure

In order to investigate the microstructure of the material in weld zones, the cross-section of the welded sample with the narrow gap (10 mm) and small chamfer angle ($\alpha = 15°$) is divided into 13 areas as indicated in **Fig. 5**.

The welded specimen is cut into three parts using a wire electrical discharge machine. These parts are numbered from bottom to top as M_i1, M_i2, and M_i3 (where i is the i^{th} welding experiment, the second index 1, 2, 3 is the according number of the layer from bottom to top of the weld joint). Positions 1, 2, 3 are located at the weld zone center. Positions 4, 5, 6, 7, 8, 9 are on the boundary region between the weld metal and the HAZ. Positions 10, 11, 12 are selected in the HAZ zone. Finally, position 13 indicates the base metal zone near the HAZ.

In this study, the microstructures of 13 positions from 3 different experiments are investigated. In detail, the microstructure properties of following positions and procedure parameters are examined: positions 1, 4, 7, and 12 of experiment 3 ($U_w = 28$ V, $V_t = 4$ m/h, $V_r = 20$ rpm; $M_3 1$); positions 2, 5, 8 and 11 of experiment 2 ($U_w = 26$, $V_t = 4$ m/h, $V_r = 20$ rpm; $M_2 2$); and positions 3, 6, 9, 10, and 13 of experiment 8 ($U_w = 26$ V, $V_t = 8$ m/h, $V_r = 20$ rpm; $M_8 3$).

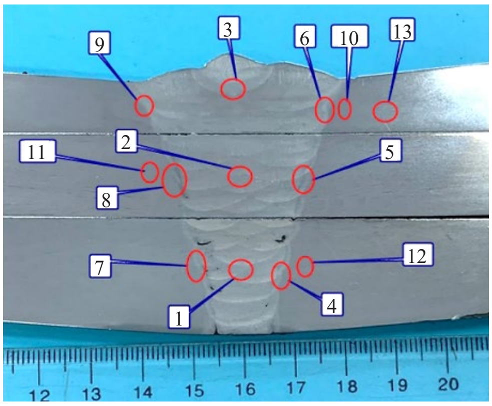


Fig. 5. Examined positions of the cross-section of a butt-welded specimen for the thick plates with the narrow gap (10 mm), bevel angle (α = 15°)

3. Results and discussion

3. 1. Microstructure characteristics of narrow gap welds

Fig. 6 shows the microstructure properties of the 13 positions on the cross-section of the weld joints. The microstructure properties of the welding center area, including positions 1, 2, and 3, were examined.

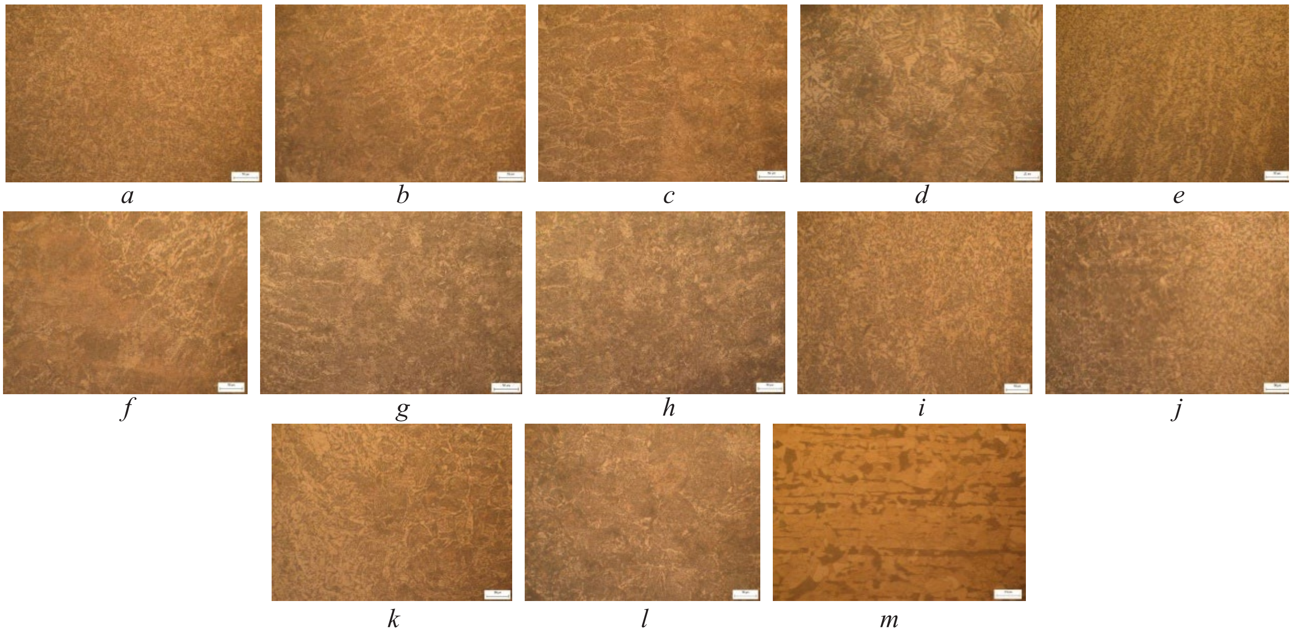


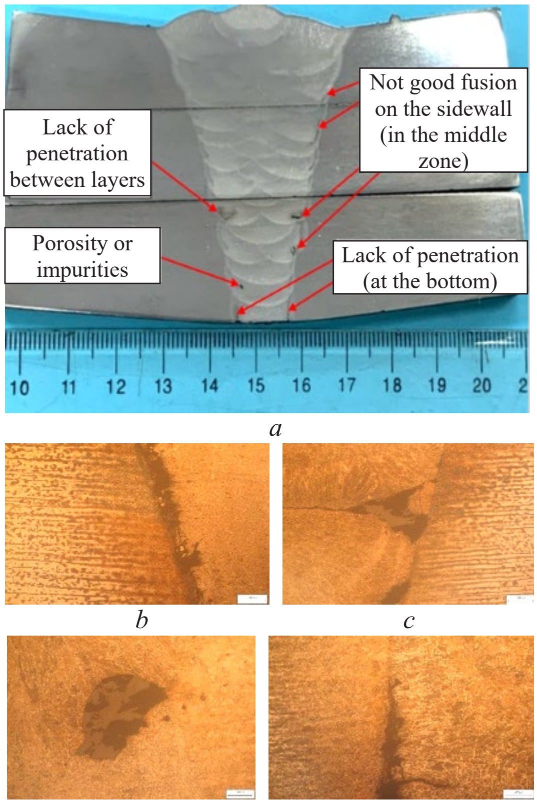
Fig. 6. Microstructure of narrow gap welding at 13 positions corresponding to 4 regions of 3 welded samples (magnification = 200): *a* – position 1; *b* – position 4; *c* – position 7; *d* – position 12; *e* – position 5; *f* – position 5; *g* – position 8; *h* – position 11; *i* – position 3; *j* – position 6; *k* – position 9; *l* – position 10; *m* – position 13.
Note : a–d from experiment 3 *(*$M_3$1*); e–h from experiment* 2 *(*$M_2$2*); i–m from experiment* 8 *(*$M_8$3*)*

Fig. 6, ***a, i*** show that the grain structure in the central region is relatively uniform and fine. The grain size of this region is smaller than that of the other regions. However, the microstructures in **Fig. 6, *e*** indicate fine and columnar grain structures. This can be explained by improper cooling conditions during welding or intermittent performance during welding. **Fig. 6**, ***b, f, j*** show the microstructures at the boundary between the weld metal zone and the HAZ on the right side of the joint. **Fig. 6, *c, g, k*** demonstrate the microstructures at the boundary between the weld metal and the HAZ on the left side of the joint. A good penetration between the weld metal and the base metal on both sidewalls of the joint without defects can be observed. The material structures on the right and left parts are quite similar. The separated zones can be observed clearly, and the grain structure in the region far from the weld center is coarser and larger in size. **Fig.6**, ***d, h, l*** show material structures in the HAZ. The grain size is coarse and larger than the regions near the weld center. The influence of evaluated temperature on the HAZ is clearly revealed. **Fig. 6,** ***m*** shows a typical microstructure of the base metal. In summary, based on assessing microstructures of welding metal, the quality of welding is good. It can completely meet the basic requirements of welded steel structures [19].

3. 2. Defects of narrow gap weld

During the experiment, a small number of samples encountered defects in the weld joints. **Fig. 7** shows the locations and microstructures of defects of experiment 21 with $U_w = 28$ V, $V_t = 8$ m/h, $V_r = 20$ rpm. The defects include lack of interlayer penetration, lack of weld fusion on the sidewalls, porosity (or impurities), as shown in **Fig. 7*, a*, *b*** illustrates the microstructure at the bottom part of the weld where the weld quality is poor due to poor penetration. **Fig. 7**, ***c*** shows a lack of metal penetration between the weld layers. **Fig. 7**, ***d*** demonstrates that the defects are caused by lacking interlayer penetration and weld fusion on sidewalls of specimens. **Fig. 7**, ***c*** shows visible porosity (or impurities) existing in the weld zone [20].

Fig. 7, ***a*** shows that the defects mainly appear at the bottom part of the joint. This is because the joint structure with too-narrow gap and small chamfer angle restricts the space required for the necessary movements of the welding tip leads to a poor welding quality. The other defects, such as porosity and non-penetration in the middle part of the joint, could be due to inappropriate welding parameters.



a

b *c*

d *e*

Fig. 7. Defects of narrow gap welds:
a – Positions of defects; *b* – Defects due to lack of fusion on the sidewall; *c* – Defects due to low penetration between layers; *d* – Defects due to low penetration between layers and lack of fusion on the sidewall; *e* – Defects due to porosity (or impurities) (magnification = 50)

It can be observed that the number of defects in this study is higher than that obtained by welding narrow gap steel plates with a small thickness of 25 mm and a large bevel angle of 30° [21]. Moreover, the joint structure of the weld has a strong influence on the welding quality in the narrow-gap weld. This is the typical challenge in narrow-gap root welding [22, 23].

Non-destructive evaluation confirmed the quality of welds. However, a small number of welded samples still present defects such as lack of interlayer penetration, lack of weld fusion on the sidewalls, porosity (or impurities). Therefore, optimization of welding process parameters to achieve high welding quality needs to be further studied. On the other hand, from the results of weld defects, it is necessary to consider the effect of other factors (such as cooling conditions, dwell time when the arc approaching the sidewalls) on the weld quality.

The micrography analysis certified the proposed welding process, including the initial hypothesis and assumptions, excluding the experiment 21. In this case the typical defects happened probably due to the elevated heating in weld pool require more rotation of welding tip to provide the smooth and stable dynamic environment for good melting efficiency at the side walls of weld.

The limitations of this study is the data on the value of the microhardness in all specific points, which additionally explain the mechanical properties and serve as the accompanied structure transitions in terms of the metallurgy.

4. Conclusions

In this study, butt welding of heavy thick steel plates (50 mm) with a narrow gap and small bevel angle (15°) was performed using the MAG welding method. Microstructures of 4 regions in the joints showed the change in shape and size of the grains following the theory of butt welding.

By using the new process, the melting conditions were improved, limiting the welding defects. The findings proved the welding quality is similar in case of narrow gap but the chamfer angle is twice lower in comparison with the previous publications, leading to save the production costs.

For the mild steel constructions with heavy design of weld joint, the MAG welding method is successfully recommended with the shielding gas 100 % CO_2, preventing the splats and infusion, porosity as typical disadvantages of narrow gap welding.

In the future it is useful to widen the involving parameters such as the cooling condition, the inclined angle of welding tip, the feeding rate of wire to have the full real welding environment in industry.

Conflicts of interest

The author declares that he have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

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