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IDENTIFYING THE INFLUENCE OF TRANSIENT THERMAL TENSIONING TREATMENTS ON MINIMIZING DISTORTION AND IMPROVING FATIGUE BEHAVIOR OF STEEL WELDED

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Due to the cost efficiency of welding repairs, the use of transient thermal tensioning (TTT) has begun to be applied to minimize distortion and residual stresses, particularly on thin plates. However, it requires a long preheating time especially on large structures, so that the efficiency of welding process cannot be maximized. Application of TTT treatment using flame heater on TTT treatment which require no preheating time so that welding efficiency can be increased. The aims of this study are to investigate the TTT treatment in reducing distortion, investigate the effect of TTT treatment on tensile strength and hardness, investigate the microstructure and its effect on tensile strength and hardness, investigated the effect of TTT treatment on fatigue crack growth rate. In this research, TTT treatment was performed by flame heating on the both side of weld line integrated in welding process. Temperature in both side plates were controlled and measured using thermocouple. The tests on the weld joints were carried out including distortion measurement, microstructure examination, hardness measurement, tensile test and fatigue test. Results showed that the TTT (–60) treatment is the most effective in decreasing the longitudinal distortion which placing the flame heating a 60 mm behind welding torch. It tends to increase the tensile strength of weld metal supported by its increasing hardness. The increase in the percentage of the acicular ferrite phase is linearly related to the tensile strength and hardness of the weld joint. The fatigue behavior could be improved by TTT treatment (–60) which is associated with the effect of decreasing residual stress in the weld metal region. This treatment is the best parameter in an effort to increase the welding efficiency of the TTT method

***Keywords:** TTT treatment, distortion, fatigue behavior, flame heating, welding efficiency, welding process, steel welded, thin plates, microstructure, tensile strength*

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1. Introduction

Welding techniques have been widely used to joint metal to metals, such as those in construction and machining industries i. e: automotive industry, ships, aircraft, bridges and others. Welding techniques are selected in the production process because it can save production and operational costs, applied easily and meet the expected strength requirements. The development of welding technique in this thin plate can be a challenge for researchers in optimizing and improving welding efficiency [1].

Common problems encountered in thin plate welding in the ship industry are distortion and residual stresses due to welding thermal. Thermal welding produces a thermal stress capable of altering the shape and size of the workpiece. It is also capable of rising post-weld tensile stress in such a way the industry is disadvantageous. Repairman is needed to fix the distortion so that it effects more time and cost in every ship production.

Control of distortion and residual stress is very important, since both of them reduce the quality of welding results. The controlling can be conducted by welding treatment although it requires additional welding process. Some researchers have applied welding treatment and its test by mechanical test, residual stress test, and perform FEM simulation and numerical analysis. Treatment in welding remains an interesting topic of discussion and needs innovation to solve the welding problem [2].

The common treatments in welding that used to reduce distortion and residual stress especially on thin plate are mechanical treatment and heat treatment, performed during in- process welding or post-welding. Mechanic treatment on welding is conducted by giving mechanical force during welding process by stretching method and vibratory welding condition (VWC) method. Stretching method is done by pulling the workpiece with a certain load during welding. This method can reduce the distortion in the plate about 60 % [3]. The VWC method is performed by vibrating the workpiece during the welding process so as to effectively reduce residual stress and distortion [4, 5]. Furthermore, heat treatment on welding is done by giving heat treatment during welding process. The double side arc welding (DSAW) method using TIG heaters on the back side of the workpiece can significantly reduce the distortion level [6]. The static thermal tensioning (STT) method is carried out by static heating while the welding process is able to minimize welding distortion effectively [7].

The transient thermal tensioning method is a heat treatment technique on welding for controlling residual stress and distortion by providing heat on both sides of the welding area placed front, side or back with a moving heat source. This method can change the temperature gradient during welding so that affect to distortion and residual stress. In addition to controlling distortion and residual stress, the use of TTT on welding can decrease the rate of fatigue crack propagation [8, 9].

According to researchers [10], TTT with side (secondary) heaters placed in front of the welding flame generates the necessary thermal stresses that lower compressive weld residual stress below the threshold value, preventing buckling. Other researchers [11] have looked into the impact of secondary heat source placement in friction stir weld joints that have undergone TTT treatment. According to the findings, when the heaters are positioned in front of the tool, the thermal tensioning impact is probably more potent from the standpoint of fatigue performance.

Although secondary heating is typically carried out using burners or resistive heating bands, electron beams have been used as secondary heat sources in front of the electron beam welding (EBW) gun. The results show that temperature distribution resulting from multi-beam heating is more uniform, leading to thermal tensioning, which lowers the weld residual stress [12]. By adjusting the burner separation distance and side heating temperature, researchers [13] have recently sought to manage welding distortion and residual stress via thermal tensioning.

In the last decade, research about TTT on welding began intensively to resolve the problem of distortion and residual stress. This method is quite effective in reducing the level of distortion and residual stress, but the disadvantage of this method is that it requires a long preheating time before welding process, especially for welding large structures [14]. Long heating causes the efficiency of the welding process to become less efficient. Studies on the fatigue behavior of welded joints with TTT treatment have not been presented completely by previous researchers. Therefore, studies that are devoted of the fatigue behavior of TTT-treated welded joints are scientific relevance.

2. Literature review and problem statement

Researchers [15] application of TTT to the double fillet welding of ASTM A36 steel utilized two propane-fueled flame heaters as auxiliary heating sources. They prevented buckling distortion by lowering the compressive residual stresses at the free edges of the panel below the critical value. The minimum distortion was obtained when the auxiliary sources were 193.5 mm from the weld centerline and 145 mm in front of the GTAW source, according to researchers [13] investigation into the impact of auxiliary heat source positions on the residual stress and distortion of 2 mm thick DP600 steel butt joints when using the GTAW process. Based on the application of TTT using a flame heater which is applied to the field of welding workpieces, there is a slight weakness, namely the heating energy is quite large. The area of the welding workpiece is heated evenly so that the energy required is directly proportional to the area and thickness of the workpiece.

To show the validity of transient thermal tensioning (TTT) in mitigating welding-induced buckling, researchers [10] performed a series of thermal elastic plastic (TEP) FE simulation and associated experiments. In the literature, this method decreased residual stress below the crucial buckling level. In order to prevent buckling distortion in welded structures, researchers [8, 15] reported an experimental verification of the transient thermal tensioning (TTT) technique. The outcomes showed that once buckling distortion was removed, angular distortion appeared and could be removed using mechanical restraints. FE models of transient thermal tensioning (TTT) were created by researchers [16] for certain test panel designs and representative production panels. The research presented shows the results of distortion testing and mechanical testing but fatigue testing has not been discussed in depth.

In order to reduce welding distortion for a T-joint by high temperature transient thermal tensioning (TTT), [17] used a FE method based on the thermal elastic plastic (TEP) FE approach. It was determined that the mechanical nature of the transient thermal tensioning (TTT) technique for reducing welding distortion does not result from temperature couplings, preheating, or delayed cooling processes. The AA5083-H116 joints were subjected to the transient thermal tensioning (TTT) approach by Ilman et al. [11], and the findings were confirmed by comparable welding tests [18]. The use of finite elements can help predict a treatment in welding but requires in-depth experimental research data so that the parameters presented can be proven and become a reference for further research.

By simultaneously preheating several beams on both sides of the weld, [19] proposed a novel electron beam welding technique that reduced buckling distortion by 80 %. Researchers [20] hybrid technique for reducing welding residual stress and distortion combined transitory thermal tensioning with following extensive cooling. The reductions of the welding residual stress and joint distortion reached 65 % and 58 %, respectively, in their research using this hybrid technique to regulate the temperature field and longitudinal residual stress.

The process of preventing welding-induced buckling with transient thermal tensioning (TTT) based on Trailing Intensive Cooling (TIC) was elucidated by researchers [21]. The residual stress reduction reaches 23.8 % with applying TIC in the FSW process and maximum distortion workpiece under TIC is 52.3 % of workpiece under conventional cooling. Buckling distortion mitigation is brought about by the thermal stretching brought about by additional heat sources, which reduces residual plastic strain and tendon force. The level of reduction of residual stress and distortion achieved in this study is still not optimal, but the use of a coolant that does not use heat energy can be an option in thin plate welding.

All this allows to assert that it is expedient to conduct a study on TTT treatment of low carbon steel welding for minimizing distortion and improving fatigue behavior. Improvements to the TTT method in this study are supported by distortion testing, mechanical testing and fatigue behavior testing which can be considered in the application of the TTT method in the future.

3. The aim and objectives of the study

The aim of this study is to identifying several variables that determine the level of effectiveness of the TTT treatment in the welding process against changes in distortion, mechanical properties and fatigue behavior of low carbon steel materials. This will make it possible to obtain the best TTT treatment variable data which is expected to be used for thin plate welding applications such as in automotive construction, ships and others.

To achieve this aim, the following objectives are accomplished:

– investigate the TTT treatment that is most effective in reducing distortion;

– investigate the effect of TTT treatment on tensile strength and hardness;

– investigate the microstructure and its effect on tensile strength and hardness;

– investigated the effect of TTT treatment on fatigue crack growth rate.

4. Materials and Methods of Research

4. 1. Object and hypothesis of the study

The object of research is A36 carbon steel plates joint by Metal Inert Gas (MIG) welding. The dimensional of the plates were of 400×100×4 mm, each of plate was grooved in one side of longitudinal direction with angle of 30°. The chemical compositions of A36 steel and filler metal are given in Table 1.

Table 1

The chemical composition of A36 steel, filler metal (wt %) [22]

Materials	C	Si	Mn	P	S	Cu	Ni	Cr	Fe
A36 steel	0.159	0.243	0.733	0.023	0.003	0.0137	0.016	0.042	Bal.
Filler metal	0.116	0.430	0.859	0.02	0.011	0.0834	0.014	0.035	Bal.

The results of testing the chemical composition of A36 steel and filler metal in Table 1 show the suitability of the chemical composition, especially the percentage of carbon between the parent metal and filler metal. This indicates a welding procedure that is in accordance with the standards for the use of electrodes.

The main hypothesis of this study is that there is a significant reduction in welding distortion, an increase in the mechanical strength of the weld and an increase in fatigue behavior on the main parameters found in this study. This study assumes that the steel material has a homogeneous composition and the same strength in all loading directions. Strength analysis is simplified by ignoring human errors and environmental factors. This research was carried out with 3 repetitions of experiments for each test variable to simplify testing and analysis.

4. 2. Welding process

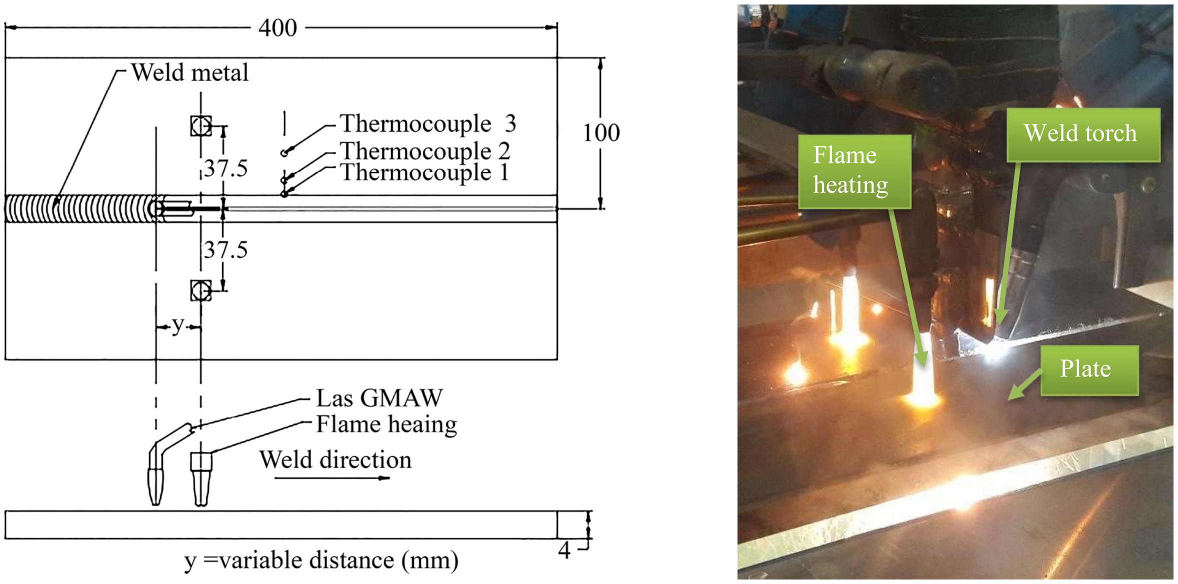
Transient thermal tensioning treatment in this study used flame heating sprayed with a torch following GMAW welding travel motion. The flame heating distance of the welding torch that was used as the TTT treatment variable, i. e:

a) flame heating in front of the welding torch of 80 mm further was called TTT 80;

b) flame heating in front of the 40 mm welding torch was called TTT 40;

c) flame heating behind a welding torch of 60 mm was called TTT (60). Flame heating that was placed in front of the weld torch was termed as preheat treatment and behind the weld torch was termed as post-heat treatment. The GMAW welding process with TTT treatment as a post-heat treatment on carbon steel A36 was shown in Fig. 1.

Placement of flame heating in the transverse direction was placed at 37.5 mm from the weld center that was applied on the right and left of the weld line. The weld thermal cycle was obtained by placing the thermocouple at 2 points on the workpiece spaced 5 mm and 30 mm from the center of the weld. At the 30 mm thermocouple distance, the maximum temperature that was measured was referred to as the plate temperature at this TTT treatment because it is closest to the flame.



a *b*

Fig. 1. The schematic of transient thermal tensioning treatment: *a* – experiment design; *b* – experiment process

4. 3. Measurements of distortion

Distortions were measured by a dial indicator gauge that gave 0.01 mm accuracy. The point of distortion measurement was marked at every distance of 20×20 mm. The distortions along the longitudinal direction (out-of-plane distortion) were plotted by taking the average of the distortion on transverse distortions.

4. 4. Microstructure Examination

The optical microscope with 100×magnification was used to examine the microstructure of the weld joint. Before examination, Before the sanding, polishing, and etching process were done on the specimens. Examinations were carried out in two important area i. e. weld metal (WM) and heat affected zone (HAZ). The picture of microstructure was analyzed by ASTM method [23] that measure and calculate of the particle types in the cross-linear marked.

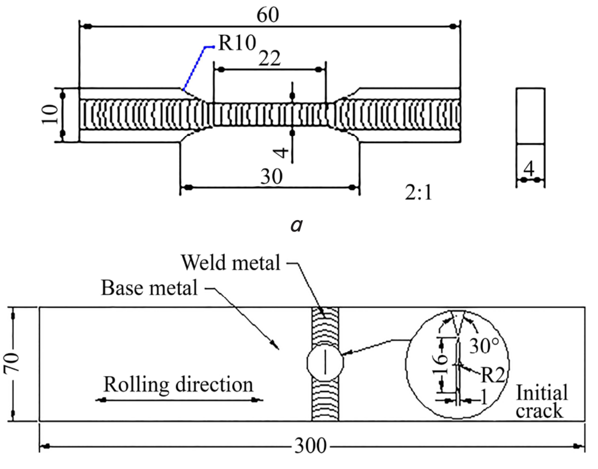
4. 5. Tensile and fatigue tests

Tensile tests were carried out using a machine with a load of 2 tons on the longitudinal directions. The standard JIS Z2201 was used to the reference of the specimens' dimension that shown in Fig. 2, *a*. The result of tensile tests were maximum strength and yield strength that were calculated from the maximum load and 0.2 % of the load in load-displacement diagram.

The fatigue tests were carried out servo pulse machine with a stress ratio (*R*) of 0.1. The ASTM E 647 standard test was used to reference of specimens' fatigue test. The fatigue growth crack test (FGCR) is determined by derivate the crack length-cycles (*a–N*) diagram to *da/dN–*Δ*K*. Furthermore, fatigue crack propagation was analyzed by Paris Law as shown in (1):

$$\frac{da}{dN}=C\left(\Delta K\right)^{n}, \tag{1}$$

where *da/dN* is fatigue crack growth rate, *C* and *n* are Paris constants and Δ*K* is stress intensity factor.



a

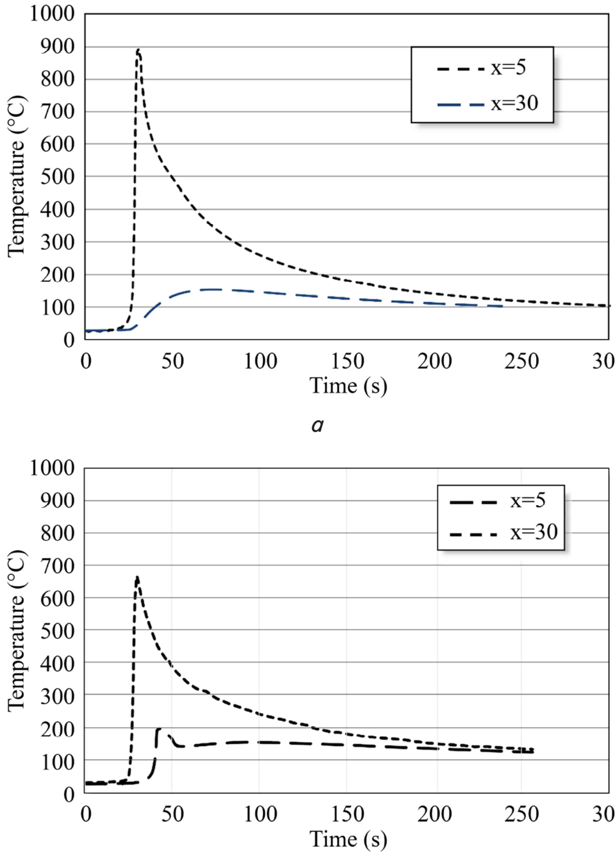
b

Fig. 2. Schematic of the specimens tested: *a* — longitudinal tensile test; *b* — fatigue test [22]

5. Results of investigating the transient thermal tensioning treatment

5. 1. Thermal cycles and welding distortion

To find out the cause of welding distortion, it is necessary to investigate the thermal cycle that occurs in the area around the welded joint. Fig. 3 shows the welding thermal cycle during the welding process with TTT treatment. Based on the chart, flame heating can change the temperature distribution in the weld area and its surroundings, especially at the points within 30 mm of the weld line. The two thermal cycles as welded and the TTT treatment (–60) were compared to obtain the character of the thermal cycle and the tendency of the flame heating pattern.



a

b

Fig. 3. Welding thermal cycle at several measuring points around the welding line: *a* — as-welded condition [22]; *b* — Transient thermal tensioning (–60) treatment

At a point of 5 mm from the weld center, it can be seen that the TTT treatment does not have a significant impact on the thermal cycle so it tends similar to the as-welded condition. This argument can be explained by the cooling time (Δ*t*8/5) of the TTT treatment and the as-welded condition at the point spaced 5 mm from the weld center has similar each of 20 seconds and 19 seconds. This phenomenon indicates that the area close to the weld line is not much affected by TTT treatment.

The graph cycles thermal TTT treatment of welding shows the plate temperature soaring to a temperature of 200 °C at a point of "*x*=30 mm" from the weld center which affects the heat distribution. In as welded the thermal cycle fluctuations were seen which increased slowly to a temperature of 200 °C and then slowly decreased, while in the TTT treatment, the fluctuations of the thermal cycle were seen to increase rapidly to a temperature of 200 °C then decreased slowly. With the TTT treatment, the area around the weld which is 30 mm distance from the weld center obtains the heat input that effect the reduction of plate temperature fluctuations.

Fig. 4 shows the distortion level of the weld test object in the longitudinal direction with the TTT treatment in some variation of the flame heating distance. The as welded, TTT 80, TTT40, and TTT(−60) compared the level of distortion by measuring the dial indicator at each test point of the weld specimen. The comparison results are used to determine the minimum level of distortion in each treatment and the pattern of distortion that occurs in the workpiece.

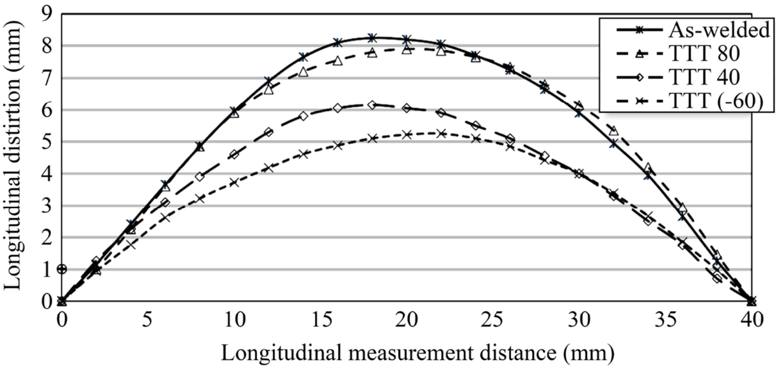


Fig. 4. Longitudinal distortion along weld direction for as-welded and transient thermal tensioning treatments

Based on Fig. 4, it is known that TTT treatment can reduce distortion especially in longitudinal direction. Minimum distortion levels occur at TTT treatment (−60) of 5.24 mm, while the maximum distortion occur at as-welded conditions of 8.20 mm. This phenomenon due to TTT treatment (−60) as post heat treatment can reduce the stress fluctuation well. Another treatment of TTT 80 does not affect distortion significantly. This indicates that TTT treatment as a preheat treatment is less significant in reducing stress fluctuations. Thus, the TTT treatment that acts as a post heat TTT (−60) is the best treatment in reducing the level of distortion. The mechanism for reducing welding distortion due to TTT treatment can be seen in Fig. 5.

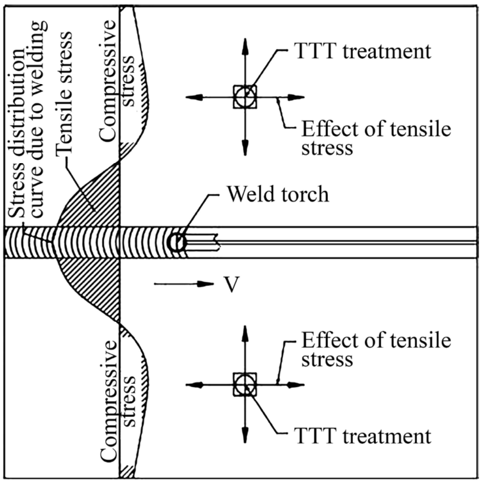


Fig. 5. Mechanism of transient thermal tensioning treatments effect on distortion

5. 2. Tensile stresses and hardness distribution

A tensile test on weld specimens of TTT treatment was carried out to determine the maximum tensile strength of weld metal and tensile test character. The as welded, TTT 80, TTT40, and TTT(−60) were compared for their maximum tensile strength and the results were used to determine the maximum tensile strength and determine the area of the weld where the fracture occurred. The results of tensile testing are shown in Fig. 6.

Graph Fig. 6 shows the tensile strength of longitudinal direction in the treatment of TTT 80 and TTT 40 was no significant change (less than 5 %) compared to the tensile strength of as-welded. However, in TTT treatment (−60) was a significant increase in the tensile strength of welding to 581 MPa or an increase of 7.8 % compared to the as-welded condition. This indicates that the TTT (−60) treatment with the heater behind the welding torch acting as post-weld tends to improve tensile strength compared to acting as preheat in TTT 80 and TTT 40.

The results of the tensile test showed that the TTT treatment did not significantly change the tensile strength of the material, because the measured strength was the strength of the base metal, considering that fracture occurred in the base metal. The tensile strength of TTT treatment is linear with the value of hardness for each treatment. The increase in tensile strength in the TTT (−60) treatment was linearly related to the increase in the percentage of AF and an increase in hardness levels of the weld metal supported by the findings of the authors [24].

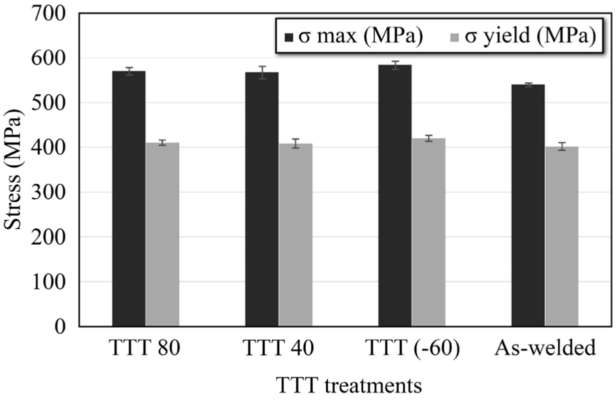


Fig. 6. Tensile strength of weld joints in the longitudinal direction

Measurement of hardness in TTT treatment and as-welded specimens were carried out on 4 welding zones, namely weld metal (WM), Coarse Grain-HAZ (CG-HAZ), Fine Grain-HAZ (FG-HAZ) and base metal (BM) displayed in a graph of the distribution of hardness in Fig. 7.

As seen in Fig. 7 all TTT treatments increase the value of hardness, especially in WM. This is because the TTT treatment with flame heating in the parent metal area has the effect of increasing the total heat input, which has an impact on increasing the value of hardness in the WM region. When associated with microstructure analysis in the WM area in Fig. 7, the increase of hardness in the WM area was due to an increase in the percentage of AF while the GF and WF decreased. This finding is consistent with other authors [25] that hardness is strongly influenced by microstructure.

Effects of TTT treatment also increase the hardness in the FG-HAZ and BM areas. In these two regions, the TTT 40 treatment tends to have a higher level of hardness than other TTT treatments. This is because the TTT 40 treatment has the closest flame heating distance to the welding torch so that the increase of the heat input is higher than other treatments. The increase of the hardness in the FG-HAZ and BM areas was due changes in grain size to smaller on the microstructure due to TTT treatment.

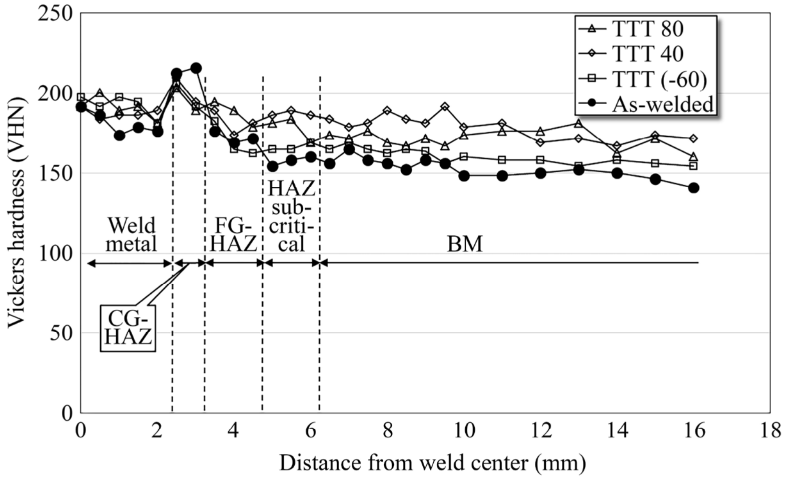


Fig. 7. Hardness distribution on A36 steel weld joints

5. 3. Microstructures

Observation of microstructure was carried out on specimens produced by TTT treatment with variations in flame heating distance, namely TTT 80, TTT 40 and TTT (–60). The results of microstructure observation conducted on the weld metal (WM) and heat affected zone (HAZ) areas are shown in Fig. 8, 9.

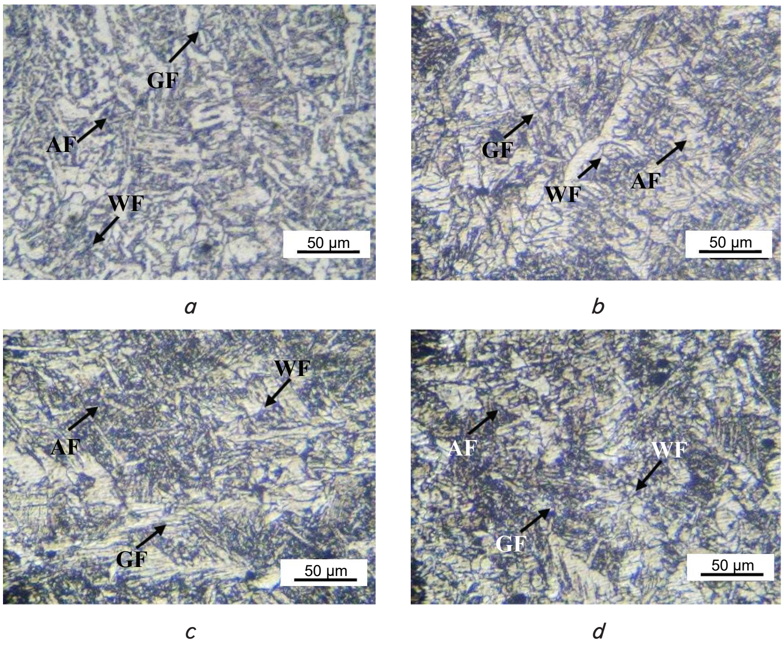


Fig. 8. Comparison of Microstructures in the weld metal area: *a* – as-welded; *b* – transient thermal tensioning 80; *c* – transient thermal tensioning 40; *d* – transient thermal tensioning (–60)

Fig. 8 presents comparison of microstructures in weld metal areas that show similarity phase. The formed phases in weld metal include acicular ferrite (AF) with a clear grain boundary shape and a rather dark color, grain boundary ferrite (GF) with bright lines and Witmanstatten ferrite (WF) with dendritic shapes with a rather dark color. The use of TTT treatments changes on size and volume of them. Changes in size and volume tend to improve the microstructure which is indicated by an increase in the AF phase which has better strength than other phases.

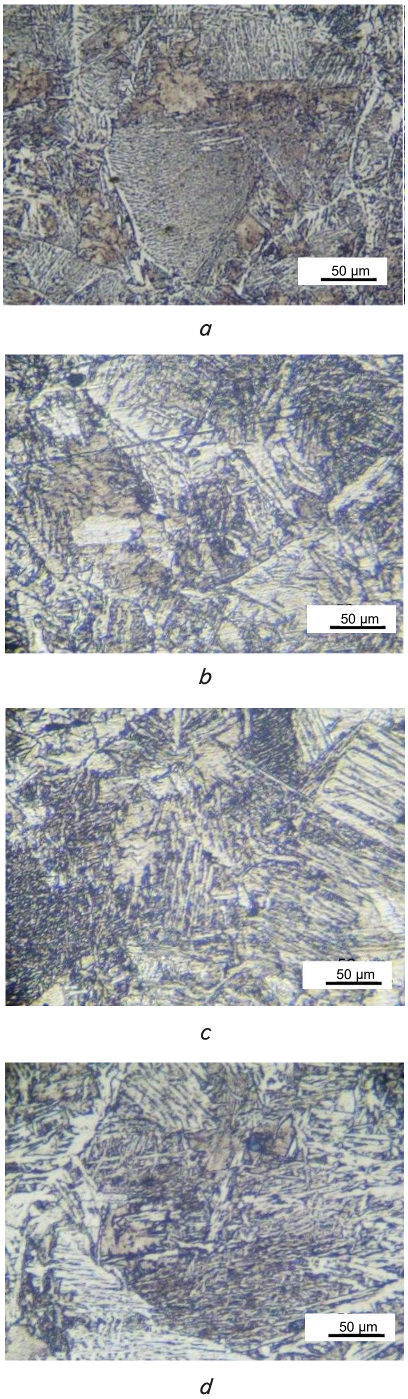


Fig. 9. Comparison of microstructures in the HAZ area: *a* – as-welded; *b* – transient thermal tensioning 80; *c* – transient thermal tensioning 40; *d* – transient thermal tensioning (–60)

Fig. 9 shows the microstructure in the HAZ area. The figure shows changes in grain size and volume due to TTT treatment. The change in grain size is caused by the growth of granules due to the heating process above 1100 °C [26]. The change in the percentage of microstructure by TTT treatment was analyzed using the ASTM standard volume fraction, the results are presented in graphical form in Fig. 10.

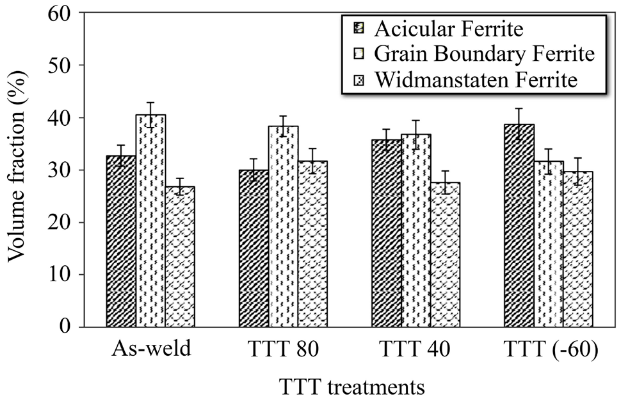


Fig. 10. Volume fraction on weld metal microstructure

The graph in Fig. 10 shows the treatment of TTT 80 and TTT 40 having almost the same percentage of AF, GF and WF as as-welded. However, TTT treatment (–60) can significantly increase the percentage of AF. This increase in AF causes changes in weld strength and tensile strength [27]. It proves that TTT treatment affects microstructure in the WM region.

The grain size changes were analyzed using grain size by ASTM method analysis, obtained graphs of TTT treatment variable function and grain size in micrometer scale as shown in Fig. 11.

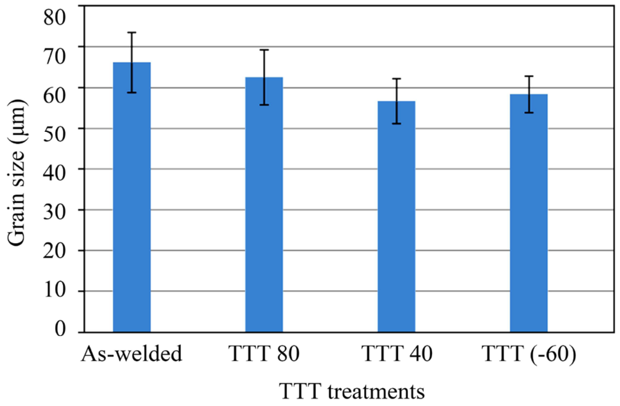


Fig. 11. Grain size on CG-HAZ

Based on the graph Fig. 11 was found that the change in grain size due to TTT treatment was most significant in TTT 40 treatment. It also has an impact on changes in hardness and strength of the CG-HAZ [28].

5. 4. Fatigue behavior

Fatigue crack propagation in the WM area with TTT treatment is displayed with a crack length diagram (*a*) as a function of the number of cycles (N) as shown in Fig. 12. The diagram shows the character of the fatigue crack propagation and the maximum cycle of the fatigue test with a certain fatigue load.

Fig. 12 shows the significant cycle difference between “as welded” and TTT (–60). The fatigue fracture cycle of “as welded” which is around 400000 cycles tends to be lower than the fatigue fracture cycle of TTT which is around 600000 cycles. It can be observed that the effect of TTT treatment can increase the number of cycles achieved during fatigue testing.

Based on the fatigue test which displays the *a-N* graph, it can be analyzed by fatigue crack propagation, which is shown in Fig. 13.

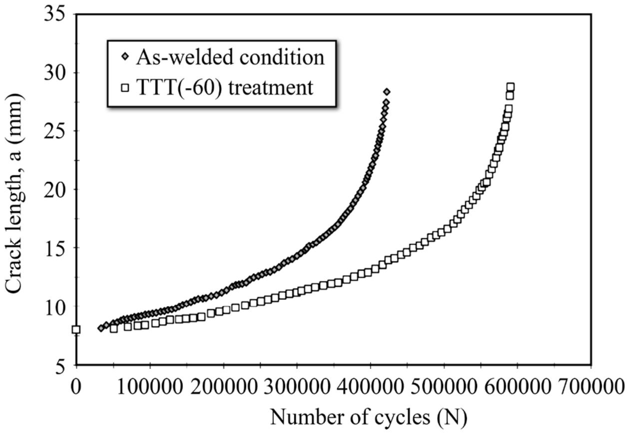


Fig. 12. The *a-N* diagram for TTT treatments in welding

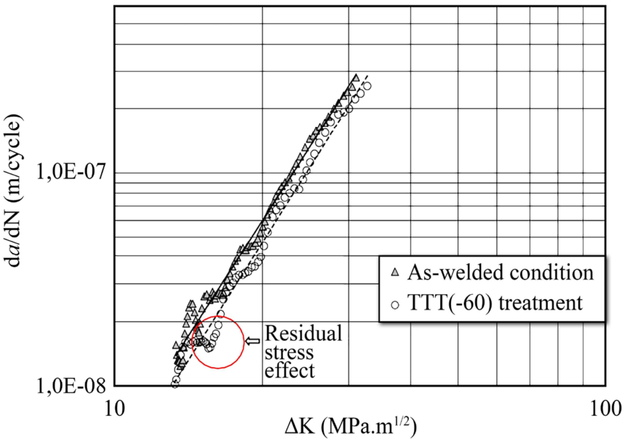


Fig. 13. Fatigue crack growth rate on as-welded and TTT (–60) treatment

By applied the Paris law, the fatigue crack growth rate can be derived from the diagram *a-N* to the *da/dN* diagram as a function of the stress intensity factor (ΔK) as shown in Fig. 13. The Fig. 13 shows that the initial crack until failure of the weld joint, the *da/dN* of TTT treatment has almost the same slope as indicated by the value of n in Table 2. However, the values of *C* on both curves have a significant difference where the value of *C* in the TTT treatment is smaller than the as-welded condition as shown in Table 2. This phenomenon shows that TTT treatment has a crack growth rate lower than the as-welded condition on all values of ΔK.

Table 2

The Paris constant based on fatigue crack growth rate diagram

Treatment	C	n
As-welded condition	1.3286E-12	3.585
TTT(–60) treatment	8.5176E-13	3.654

6. Discussion of transient thermal tensioning treatment for reducing distortion and improve fatigue behavior

The investigation results of welding distortion with TTT treatment show that the thermal cycle affects the level of welding distortion. When the TTT treatment was applied, thermal cycling fluctuations were observed which increased rapidly up to 200 °C and then decreased slowly. With the TTT treatment, the area around the weld gets heat input which has an impact on reducing plate temperature fluctuations. This has an impact on reducing distortion and residual welding stress [25]. TTT treatment can reduce distortion due to the temperature treatment in the area around the weld. the TTT treatment (–60) which heats the welding path area behind the welding torch 60 mm apart gives the effect as a post-heat treatment that can reduce stress fluctuations well and has a significant effect on distortion. The mechanism for reducing welding distortion due to the TTT treatment (Fig. 5) shows that the compressive stress due to welding will be reduced by the tensile stress due to the TTT treatment so that the stress in the area is reduced and the impact of distortion will be reduced.

The TTT treatment did not significantly change the tensile strength of the material, because fracture occurred in the base metal. It can be said that the strength of the welded joint has exceeded the strength of the base metal. This is related to the hardness distribution in Fig. 7, where the lowest hardness lies in the base metal region. This finding is supported by other authors [25] that hardness is linearly proportional to the tensile strength of the material.

Changes in the size and volume of the AF phase tend to improve the microstructure which has better strength than the other phases. The TTT treatment changed the grain size with the smallest grain size occurring in the TTT treatment (–60), while the largest grain size occurred in as-welded. This also has an impact on changes in hardness and strength where the smaller the grain size tends to increase the hardness and strength of the material.

The TTT treatment causes a change in crack propagation behavior as shown in Fig. 13. It shows an area where da/dN values decrease at low ΔK, and return to normal at high ΔK. This occurs in relation to the tensile residual stresses on the transverse direction in the TTT treatment which has a smaller value than the as-welded condition. The residual stress is able to hold the crack propagation rate to a certain stress. But at a high-stress intensity, the residual stress cannot withhold so that the propagation rate becomes normal. This is consistent with the statement of authors [29, 30] that the crack propagation rate decreases when the stress intensity (ΔK) is lower due to heat treatment on the workpiece.

Comparative analysis of the results of our study with related studies [7–9, 13–15] shows the similarity of the trend in providing a reduction effect of distortion and residual stress. This study provides additional references to the placement of flame torches in the TTT treatment welding process with a certain distance to optimize the application of TTT in thin plate welding. The effect of TTT treatment on crack propagation rate was also examined to provide updated data on fatigue load usage.

The research experiment used the TTT treatment with mechanical control which is still a limitation of this study. The use of electric controls and artificial intelligence will become more accurate controls in the future. Based on the previously summarized literature, this TTT treatment can be developed by applying controls with high accuracy, integrating TTT treatment heat sources with welding, adjusting the TTT temperature according to the material and workpiece thickness, and equalizing the workpiece temperature so that the treatment effect is more significant.

7. Conclusions

1. The TTT treatment could reduce longitudinal distortion by giving the flame heating on both sides of the weld line integrated with the welding process. The TTT (–60) treatment is the most effective in decreasing longitudinal distortion with a decrease in distortion of 36 % compared to the as-welded condition.

2. TTT (–60) treatment with a heater behind the welding torch acting as post-weld tends to increase the weld metal's tensile strength to 581 MPa or an increase of 7,8 % compared to the as-welded condition, supported by increased hardness.

3. The increase in the percentage of the acicular ferrite phase by 33 % in the as-welded condition to 38 % in the TTT treatment had a linear effect with an increase in the tensile strength and hardness of the weld joint.

4. The fatigue crack growth rate can be minimized by TTT treatment (–60) by decreasing the value of the pair constant from 1.3286E-12 as-welded condition to 8.5176E-13 in TTT treatment. This decrease also has an impact on reducing the residual stress in the weld metal area.

Conflict of interest

The authors declare that they 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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Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

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