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Research Article

THE EFFECT OF DEPTH OF FUSION ON THE BEHAVIOR OF STEEL WELDED JOINTS

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ABSTRACT

The aim of this study is to determine the effect of depth of fusion on the behavior of tempered martensite and thermomechanically rolled steel welded joints. To obtain the effect of depth of fusion on the stress and displacements, three different welded sample welded to each other by metal active gas welding method applied in PB position were prepared in accordance with the related standard. According to the welding procedure specification EN ISO 15614-1 which clarifies how samples should be welded, different current, voltage, travel speed and wire feed speed were selected for each sample. After the welding process, welded samples were subjected to visual and magnetic testing to evaluate quality of the weld seams. After the non-destructive tests, samples were cut into small pieces to measure the depth of fusion and three samples having different depth of fusion were obtained. The finite element models of these samples were created in ANSYS to evaluate the stresses and displacements of samples. The models of samples were subjected to the loads which range from 1000N to 45000N and the results were obtained under lineer- static analysis. The results of finite element analyses of samples such as stresses and displacements are compared with each other in terms of depth of fusion for each sample. It is seen that depth of fusion has remarkable effect on the behavior of welded joints.
Keywords: Depth of fusion, finite element analysis, high-strength steel, welded connection, weld design.

1. INTRODUCTION

Over the last decade, the use of both thermomechanically rolled steel (known as hot-rolled steel) and tempered martensite steel which are widely used in automotive and defense industry has increased due to their excellent mechanical properties (Spindler, 2005). Thermomechanically rolled steel and tempered martensite steel are classified to their mechanical properties and hardness values, however the lowest category of these steels mostly have high strength values in comparison to non-alloy structural steel. Metal active gas (MAG) is one of the welding methods that enables it to be preferred in especially mass production owing to robotic welding applications, high welding speed, deposition rate and non-slag welding etc (Yamamoto, 2017).

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There are lots of factors which affect life span and endurance of welded construction such as weldability, depth of fusion, weld design etc. All these factors must be considered during the design stage. Within the scope of the standards, welding procedure specifications (WPS) which describe how welding is to be performed are determined according to joint type, weld position, material thickness, chemical and mechanical properties of materials. In addition to this, depth of fusion, bead width and weld design must be taken into consideration to ensure the durability conditions of the welded construction. For this reason, depth of fusion must be determined that provide the forecast of the service life and endurance of the welded construction.

There are many studies on analysis of weld strength, residual stress distributions of welded joints, finite element analysis of welding process and distortion. Zhou et al. (2003) revealed that the relationships between quality and attributes of spot welds. Weld diameter, penetration and indentations were analyzed through the integrated numerical analysis. It was observed that the size of the heat affected zone plays an important role on weld strength due to occurring high stress concentration in the heat affected zone. Mert (2009) examined that the effect of weld toe radius and root gap on fatigue life of T-fillet welded joint by finite element analysis. In this study, it was obtained that medium sized root gap and biggest toe radius is the best design in terms of equivalent stresses. Pettersson and Barsoum (2012) presented the finite element analysis and fatigue design of a welded construction machinery component using different concepts. They concluded that linear elastic fracture mechanism and effective notch stress are the most accurate methods for estimating the service life of welded constructions. Deshmukh et al. (2014) presented the effect of weld penetration levels on fatigue life. In this study, finite element models of welded joints having different levels of penetration were subjected to the bending and tensile loads. They concluded that fatigue life of the connections fluctuates with the changing penetration levels. Dung et al. (2015) investigated the effect of weld penetration on fatigue strength of rib-to-deck welded joints in orthotropic steel decks. Welded specimens prepared as partial and full joint penetration were subjected to the fatigue loads and finite element models of the specimens were analyzed. As a result of this study, it was obtained that welded specimen comprising of complete joint penetration has shown a positive effect on enhancing the fatigue resistance of rib-to-deck welded joints. Wang et al. (2015) investigated the fatigue life of welded construction by means of hot spot stress approach. Test results were compared according to full scale specimen results and all factors affecting the stress distribution were observed. Joo et al. (2015) studied the moment redistribution of continuous composite I-girder with high strength steel. Non-linear finite element analysis for the continuous composite I-girder were analysed in this study. Kainuma et al. (2016) observed that the fatigue behavior of rib-to-deck weld root in orthotropic steel decks. Welded specimens were evaluated with regards to local stress near the welded joint, field loading tests, measurement of residual stress and fatigue tests. This study has clearly highlighted that penetration rate in the range of 0% to 75% can be beneficial for fatigue durability of this structural detail. Farafkhah and Liu (2016) investigated the effect of metal inert gas welding on the behavior and strength of aluminum stiffened plates. 3D simulated MIG welding induced heat affected zone (HAZ), residual stress and distortion fields was researched in this study. Giri et al. (2017) studied on the effect of weld groove designs on residual stresses in SS 304LN thick multipass pipe welds. In this study, finite element model of pipe welds was developed for estimating temperature distributions during the welding. Cheng et al. (2017) studied on fatigue failure of rib-to-deck welded connections in orthotropic steel bridge decks. In this study, it was focused on the fatigue cracking process and two loading cases (centric and eccentric) were considered. High cycle repeated loading was implemented and crack initiation and propagation of the specimens were observed. Yang et al. (2017) conducted the fatigue test of high strength bolts in grid structures. High strength bolts were subjected to constant amplitude fatigue tests and analyzed in accordance with the stress concentration. It was explained that geometrical stress concentration causes the fatigue fracture of high strength bolts. Zhongqiu et al. (2018) observed that the fatigue performance of rib-roof weld in steel bridge decks with corner braces. To assess the fatigue life of the construction, FEM models were created and stress distributions taking into consideration different parameters of corner brace sizes, arrangements and detail types were analyzed. In this study, it was obtained that stress of roof weld is decreased. Lan et al. (2018) studied the application of high strength steel in bridge piers under the cycle loads. In this study, the effects of various parameters including plate width-to-thickness ratio, column slenderness ratio and axial compression force ratio were investigated. As a result of work, new formulas for predicting ultimate load and deformation capacities were obtained.

As seen from the references mentioned above, studies on the effect of depth of fusion on strength and displacement of welded joints are insufficient. This paper aims to fill some of these gaps on the effect of weld penetration on behavior of the welded connection. For this purpose three different welded samples were prepared in terms of depth of fusion. Plates of sample (thermomechanically rolled steel and tempered martensite steel) were welded to each other by metal active gas welding method applied in PB position. Depth of fusion of each sample was measured on cross sections taken from the fillet welds. After the measurement, samples are numerically modeled based on the finite element method (FEM) using ANSYS. The effects of depth of fusion on joint strength and displacement of tempered martensite and thermomechanically rolled steel welded joints are identified using linear FE analysis.

2. PREPARATION OF SAMPLES

The samples consist of two steel plates (Hardox450 and Optim700MC) and these plates were welded to each other with T-fillet weld. Hardox450 and Optim700MC are known as tempered martensite and thermomechanically rolled steel respectively. Thickness of both Hardox450 and Optim700MC plates was chosen as thick as possible (8 mm) considering the depth of fusion. Schematic forms of sample are given Fig.1. Due to its carbon and alloy elements content Hardox450 has more strength than Optim700MC. Plates of sample prepared according to EN ISO 15614-1(2017) which clarifies all stages of the preparing and welding process were welded to each other by MAG method applied in PB position. Filler metal was selected according to the technical procedures recommended by steel manufacturers. In accordance with EN ISO 14175(2008), shielding gas was chosen as mixed shielding gas containing Ar, O_2 and CO_2. Welding parameters including current, voltage, travel speed and wire feed speed affect the amount of heat input, weld shape, process outcome, hardness distribution and the strength of the weld (Lu, 2005). In this study, three different welding parameters were determined to obtain the depth of fusion of samples such as 0, 1 and 2 mm. Welding parameters for each sample are given Table 1.

After the welding process, welded samples were subjected to non-destructive testing which are visual testing and magnetic testing according to EN ISO 17637(2016) and EN ISO 9934-1(2016) respectively. Within the scope of ISO 5817(2014), any defects were not observed on the weld seam and heat affected zone for each welded sample. View of the welded samples is given Fig 2. For grinding and polishing process, small welded pieces must be prepared and mounted onto bakelite. For this reason welded samples were cut into small pieces to carry out the mounting process. Welded pieces of sample C is given Fig 3. In order to observe the welded cross-section surface by visual inspection, welded cross-sections were mechanically grinded, polished and etched by nital (%3) etching reagent according to EN ISO 17639(2003) to make the weld zone visible.

After the etching, weld zone became visible and depth of fusion of each sample was measured. Based on these cross-sections, points represented the fusion line were marked to evaluate the depth of fusion of each sample. Primarily, location of the starting point (0,0) was marked and other points were marked in order to measure the depth of fusion. According to coordinate of marked points, the depth of fusion was obtained as 0 mm, 1 mm and 2 mm for sample A, B and C respectively. Welded cross-section of sample C is shown in Fig 4.

Table 1. Welding parameters for each sample

Sample	Run	Welding Process	Size of filler metal (mm)	Current (A)	Voltage (V)	Type of current and polarity	Wire feed speed (m/min)	Travel Speed (mm/sec)	Heat Input (kj/mm) (k=0,8)	Preheat Temperatures
Sample A	1	135	1	140-160	18-20	DC (+)	9	4.15	0.48-0.61	x
Sample B	1	135	1	180-200	22-24	DC (+)	12	4.48	0.71-0.85	x
Sample C	1	135	1	220-240	24-26	DC (+)	14.5	5.16	0.82-0.97	x

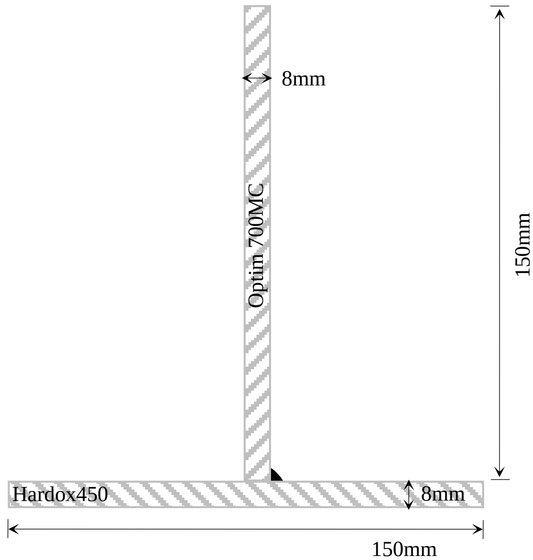

Figure 1. Schematic form of sample

(A) (B) (C)

Figure 2. View of the welded samples

Figure 3. Welded pieces of sample C

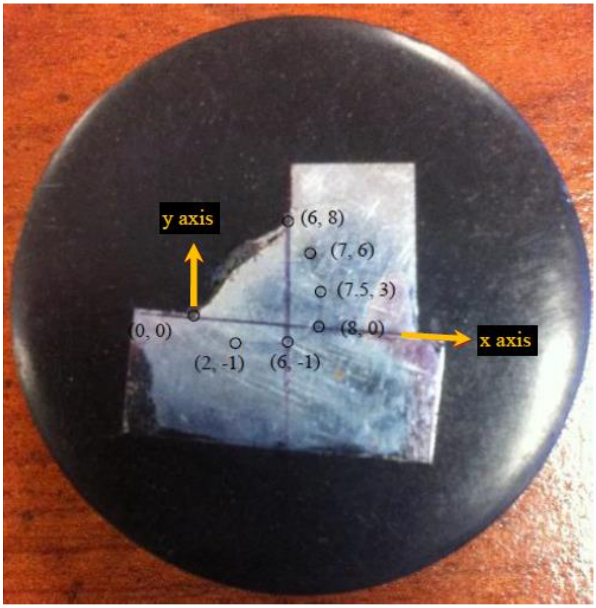

Figure 4. Welded cross-section of sample C (mm).

3. FINITE ELEMENT MODELING

Two dimensional finite element model (FEM) of samples were created by using software ANSYS (2015) and linear-static analyses of the samples are performed to obtain the stresses and deflections distribution of the along samples. For this study, Plane 182 defined by four nodes having two degrees of freedom at each node was determined to create the two dimensional FEM of samples. Before the welding, even if steel plates are placed as close as possible, the gap between the plates can be up to 1mm according to surface flatness. In this study, the gap between two plates (Optim700MC-Hardox450) was taken into consideration as 0,1mm. Welded connection and FEM of sample C are given in Fig 5 and Fig 6, respectively. According to depth of fusion three different FEM were created in ANSYS (2015). The mesh size of these FEM was selected as 1x1mm at x and y direction, since the dimensions of weld zone and depth of fusion are relatively smaller than the plates. FEM of weld zone of each sample are given in Fig 7. After the meshing process, FEM of each sample was fixed all degree of freedom at the bottom of Hardox450 plate. Static load which range from 1000 to 45000 N were applied to the top of Optim700MC plate along to x direction.

4. NUMERICAL RESULTS

In this section, principal tensile and compressive stress distribution and displacement on the plates and weld zone of all samples under all static loads were represented with detail and compared to each other.

4.1. Principal Stresses

The principal tensile and compressive stress contour diagrams of samples under 20000N along to x direction (+x and –x) is shown Fig 8 and Fig 9, respectively. Region 1 and 2 called weld toe are the junction between the face of weld and plates. Region 3 is the weld root. Region 1, 2 and 3 are shown in all contour diagrams.

In the +x direction; the maximum tensile stresses were obtained at Region 1 from sample A and B as 481 MPa and 455 MPa, however, at Region 2 from sample C as 412 MPa. The maximum tensile stresses have a decreasing trend from sample A to C. It is seen that tensile stress of sample A is higher than yield strength of weld metal in Region 1. Compressive stresses were obtained at Region 3 as -165 MPa, -211 MPa and -194 MPa from sample A, B and C, respectively. It is seen that compressive stresses obtained from all sample do not exceed the yield strength of weld metal.

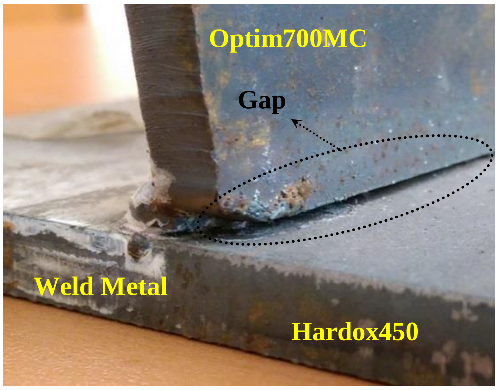

Figure 5. Welded connection of sample C

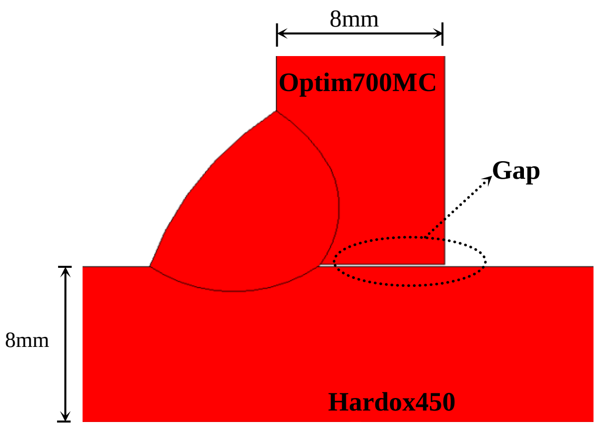

Figure 6. FEM of sample C

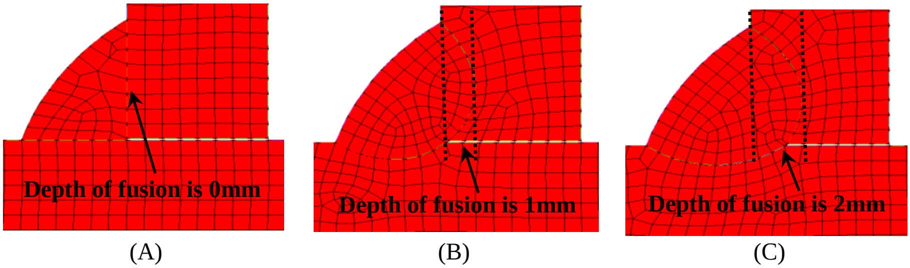

Figure 7. FEM of samples

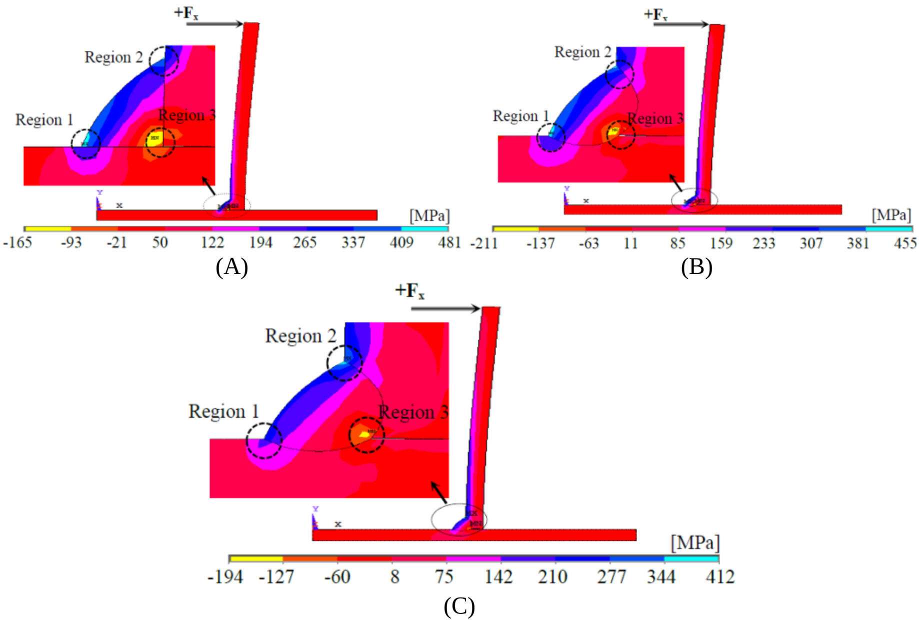

Figure 8. Tensile stress distributions of samples (in the +x direction)

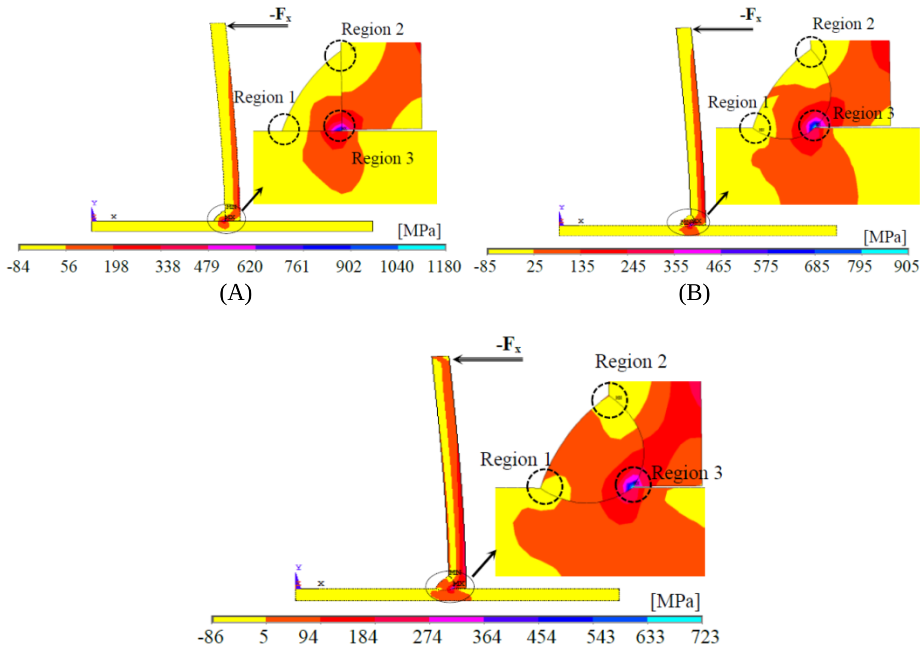

Figure 9. Compressive stress distributions of samples (in the -x direction)

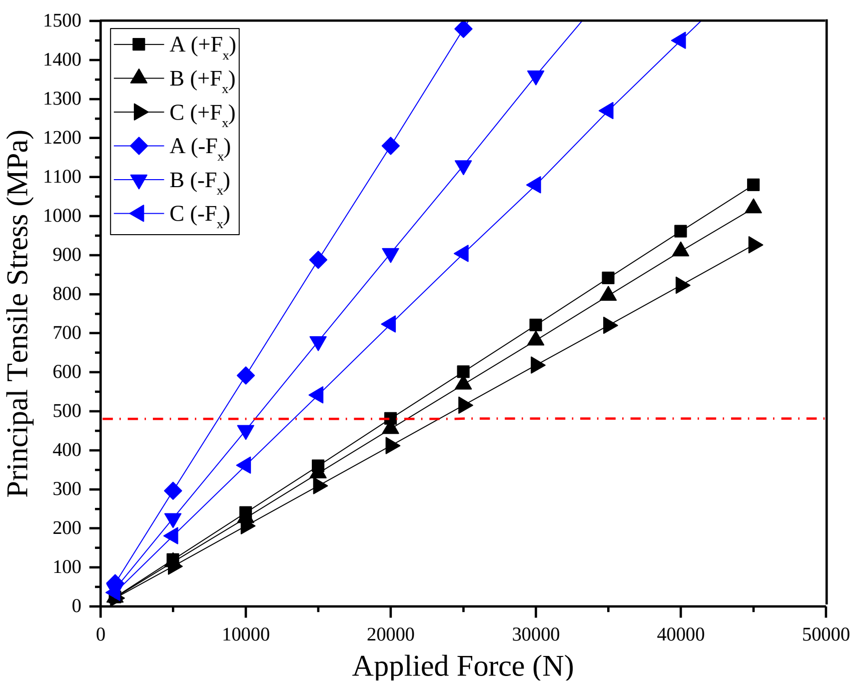

Figure 10. Principal tensile stress of samples

4.2. Displacement

Maximum displacements of each sample under the static loads were shown and compared to each other. The maximum displacement contour diagram of samples under 20000N along to x direction (+x and –x) is shown Fig 11 and Fig 12, respectively.

In the +x direction; the maximum displacements were obtained from sample A, B and C as 3.05mm, 2.90mm and 2.58mm respectively. The maximum displacements have a decreasing trend from sample A to C. It is seen that with the increasing of the depth of fusion, the maximum displacement values decrease proportionally.

In the -x direction; The maximum displacement were resulted the same values with the –x direction. 3.05mm, 2.90mm and 2.58mm were obtained from the sample A, B and C respectively. When applied loadings are taken into consideration, it is obtained that maximum displacements were occurred at the top of Optim700MC plate. As a result of this assessment, it is observed that displacement values are the free of loading direction.

In a welded construction, displacements are as important as the stresses. Plastic deformation or cracks may occur when certain values are exceeded. These values generally are related with yield stress of the materials. Static loads ranging from 1000 to 45000 N were applied along to x direction (+x and –x) and the displacement of each specimen were obtained as shown in Fig 13. As it is seen in figure, there is no change in displacement values when the directions of the applied loads are changed.

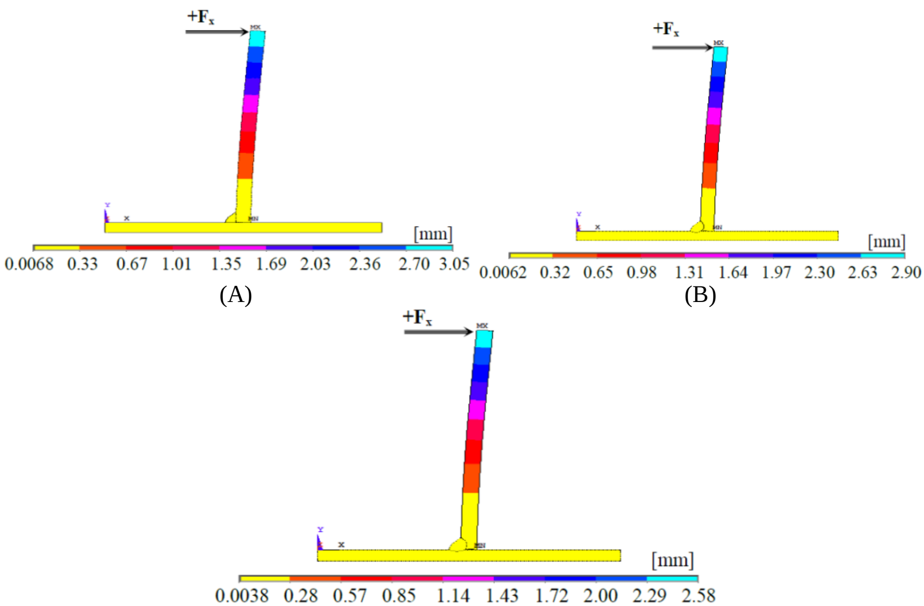

Figure 11. Maximum displacement of samples (in the +x direction)

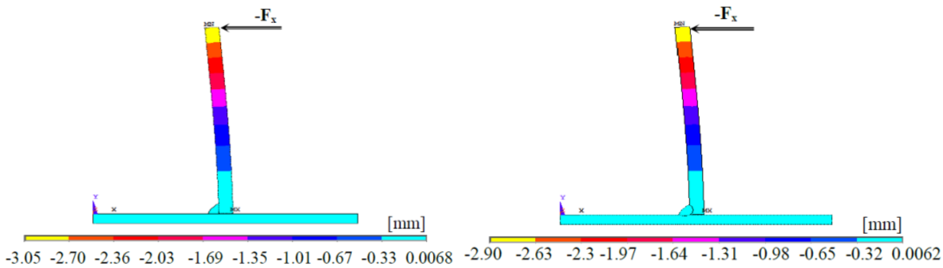

Figure 12. Maximum displacement of samples (in the -x direction)

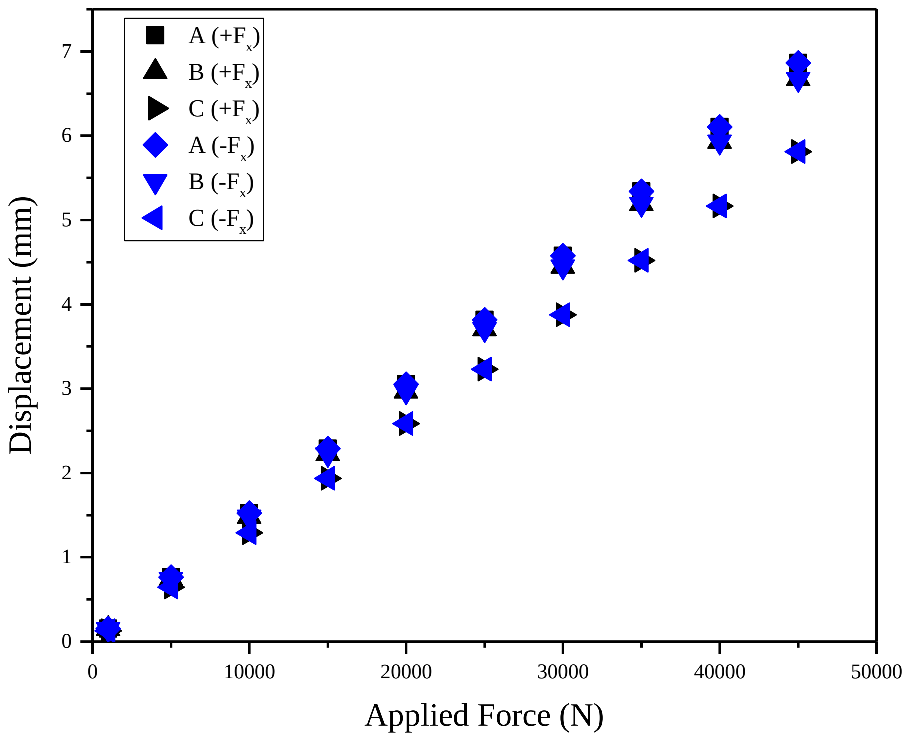

Figure 13. Maximum displacement of samples

5. CONCLUSION

This study presents an investigation about the effects of the depth of fusion on principal stress and displacement distribution of thermomechanically rolled and tempered martensite steel welded joints. Plates were welded to each other with different welding parameters to obtain different depth of fusion. After the welding process, cross sections of samples were etched to make the weld zone visible. According to depth of fusion measurements, FEM of each sample were designed and loaded by using ANSYS software. Analysis of samples is performed under the variable static loads to obtain the stress and displacement distribution. The main conclusions drawn from this analytical study are;

- The principal tensile stresses have a decreasing trend in weld zone when the depth of fusion increases. In addition to that displacements on base metal have a decreasing trend too.
- In +x direction, maximum tensile stresses were obtained on weld toe region, however, in –x direction, maximum tensile stresses were obtained on weld root region.
- When the load is applied in –x direction, the obtained tensile stress is higher than when loads applied in +x direction. However, when the direction of the applied force is changed, the displacement values remain the same.
- Sample is more durable when the load is applied from +x direction.
- The displacement values proportionally increase when the applied forces are increased.
- When the load is applied in –x and +x direction, the obtained displacement are equal to each other. Selected welded sample behave like cantilever beam.

To determine the depth of fusion with sufficient accuracy by finite element analysis provides prediction of the service life and durability of welded construction. As a result of this study, it is seen that tensile principal stress at weld zone and displacement at base metal decrease with the increasing of depth of fusion.

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