Analysis of Welding Groove Configurations on Strength of S275 Structural Steel Welded by FCAW

Araştırma Makalesi / Research Article

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ABSTRACT

The quality of welded joints depends on many factors such as welding current, voltage, welding speed, shielding gas type, and welding position. One of these factors is the welding groove design. This is because different stresses (tensile, compression, bending, etc.) can occur on the weldments. For this reason, while designing welded constructions, it is important to join them with the most appropriate welding groove configuration by considering the stresses the welded joints can be exposed to. In this study, the effect of the welding groove configuration on the mechanical and metallurgical properties of S275 structural steel joined by flux cored arc welding (FCAW) method was investigated. For this purpose, different welding groove configurations were formed for structural steel sheets. Tensile, bending, and hardness tests were performed to determine the mechanical properties of the weldments. In addition, metallographic investigations were carried out to determine the metallurgical properties of the weld zones. As a result of the tests, the effect of the welding groove configuration on the mechanical and metallurgical properties of the welded joints was determined. As a result of the microstructure studies, different structures such as grain boundary ferrite, widmanstatten ferrite and acicular ferrite were determined to form in the weld metal and coarse grained zone. It was determined that hardness of the weld metal was higher than HAZ and base metal in all welding groove configurations. As a result of the tensile and bending tests, the highest tensile and bending strengths were obtained from the samples welded by X_2 type welding groove configuration after the base metal. Furthermore, the X-type welding groove configurations showed better mechanical properties than the K-type welding groove configurations.

Keywords: Flux cored arc welding (FCAW), welding groove, mechanical properties, microstructure.

ÖZ

Kaynaklı birleştirmelerin kalitesi, kaynak akımı, voltaj, kaynak hızı, koruyucu gaz türü, kaynak pozisyonu gibi birçok faktöre bağlıdır. Bu faktörlerden birisi de kaynak ağız tasarımıdır. Çünkü kaynaklı çelik konstrüksiyonlar üzerinde farklı gerilmeler (çekme, basma, eğilme v.s) oluşabilmektedir. Dolayısıyla kaynaklı konstrüksiyonlar tasarlanırken, kaynaklı bağlantıların maruz kalabileceği gerilmeler dikkate alınarak en uygun kaynak ağız konfigürasyonu ile birleştirilmesi önem arz etmektedir. Bu çalışmada, özlü tel ark kaynak (ÖTAK) yöntemi ile birleştirilen S275 yapı çeliğinin mekanik ve metalurjik özelliklerine kaynak ağız konfigürasyonunun etkisi araştırılmıştır. Bu amaçla yapı çeliği levhalara farklı kaynak ağız konfigürasyonları oluşturulmuştur. Kaynaklı numunelerin mekanik özelliklerini belirlemek için çekme, eğme, sertlik testleri yapılmıştır. Ayrıca, kaynak bölgelerinin metalurjik özelliklerinin belirlenmesi için metalografik incelemeler yapılmıştır. Yapılan testler sonucunda kaynak ağız konfigürasyonunun kaynaklı bağlantıların mekanik ve metalurjik özelliklerine etkisi belirlenmiştir. Mikroyapı çalışmaları sonucunda kaynak metali ve iri taneli bölgede tane sınırı ferriti, widmanstatten ferrit ve asiküler ferrit gibi farklı yapılar oluştuğu tespit edilmiştir. Bütün kaynak ağız konfigürasyonlarında, kaynak metali sertliğinin HAZ ve esas metalden yüksek olduğu belirlenmiştir. Çekme ve eğme testleri sonucunda en yüksek çekme ve eğme dayanımı esas metalden sonra X_2 tip kaynak ağız konfigürasyonu ile yapılan kaynaklı numunelerden elde edilmiştir. Ayrıca X tip kaynak ağız konfigürasyonları K tip kaynak ağız konfigürasyonlarına göre daha iyi mekanik özellikler göstermiştir.

Anahtar Kelimeler: Özlü tel ark kaynağı (ÖTAK), kaynak oluğu, mekanik özellikler, mikro yapı

1. INTRODUCTION

Welding technology has developed rapidly over the last fifty years. This has led to increasingly widespread use of welded joints in sectors of machine manufacturing, automotive, construction (steel construction), energy (steel oil and gas pipelines, natural gas and petroleum exploration platforms), and pressure vessel production etc. Currently, studies on the weldability of these alloys with the development of new metal alloys continue intensively. However, welding consumables (electrode and powder, etc.) appropriate for each metal or metal alloy are not available yet. Therefore, welding consumables that can be used in welded joints of these alloys are also developed and produced in parallel with the development of new metal alloys [1]. In the gas metal arc welding (GMAW) methods, filled welding wires are used and alloy elements in these wires can only be used during the production of steel ingots used as the starting material in the production of wires. Therefore, the alloying and strengthening of the weld metal by means of the cover material of the electrodes used in the manual metal arc welding (MMAW) method cannot be performed by using the GMAW methods. In addition, since the weld zone is protected only by one shielding gas atmosphere, it is difficult to use it in open areas with air flows. A flux cored wires have been developed to solve

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this problem encountered in GMAW methods [2,3]. Thanks to the developed flux cored wires, the FCAW method combining the superiorities of the GMAW method and eliminating the negative effects of submerged arc welding (SAW) methods and covered electrodes (with MMAW) and has been used particularly in shipbuilding industry has started to be used widely [3,4].

Flux cored arc welding (FCAW) method is the same as GMAW welding method in principle. Although these methods are the same in terms of machine hardware, they are defined by different names according to the type of welding wires used [2,4]. While solid welding wires are used in the GMAW methods, wire electrodes filled with slag forming and gas generating alloy elements and deoxidation elements are used in FCAW method [3]. These elements placed in the wire perform the same function as the cover of the electrodes used in the MMAW method, thus they allow the FCAW method to be used in open areas under the air atmospheres [2,3].

In the FCAW method, the heat required for welding is produced through the arc formed between a melting and continuously fed wire electrode and the workpiece, and by the heating of resistance formed by the welding current flowing through the electrode. The welding wire is automatically sent to the arc zone, melts and forms the weld metal [5-7]. In the FCAW method, metal molten in the weld zone is protected by an externally applied shielding gas (such as GMAW) and a shielding gas atmosphere (such as MMAW) emerging as a result of a flux-core composition. When an arc is formed, these elements form welding smoke by burning and increase weld strength by alloying the weld metal [3,4,8]. Various gas combinations are used in GMAW and FCAW methods. Pure argon (Ar), pure helium (He) and CO_2 gases can be used as shielding gas alone and also as a mixture. In addition, by adding oxygen (O_2), hydrogen (H_2) and nitrogen (N_2) gases at different ratios into these gases, different gas compositions (Ar-He-CO_2, Ar-H_2, Ar-N_2, Ar- CO_2, Ar-CO_2-N_2, and Ar-He) are formed and welding processes can be performed. The types and compositions of the selected gases have a significant effect on the microstructure and mechanical properties of the joint material [6,8,9]. In addition to the shielding gas type, numerous factors affect the quality of the welded joint. These are the welding current, voltage, mechanical properties and chemical composition of the joined metal and welding wire, welding position, and welding groove configuration etc. [4,8].

S275 structural steels are widely used as structural steel tubes, construction pipe, foundation pipe, piling tube, sheet, and profiles especially in structural engineering applications and steel constructions. These steels are usually joined by arc welds during erection. Welding groove preparation is required in order to ensure the optimum mechanical properties especially in thick section steels before the welding process. Welding groove configuration facilitates welding process, provides deeper penetration, controlled cooling of the weld zone, and prevents greatly distortion during welding especially in thick pieces [10]. Studies on the effect of welding groove configuration on welding quality of the steels and other metals joined with different welding methods have been ongoing. In a study İpek and Elaldi [11] joined high-strength armor steel with different welding angles and investigated the effect of angle and geometry of the welding groove on tensile, compression, and bending strength of the welded samples. In their study, they obtained the highest tensile strength at the welding angle of 54^o and the V-welding groove geometry. They also determined that the highest compression strength was obtained at the welding angle of 48^o and the X-welding groove geometry. In a study, Li et al. [12] welded a 7075-T6 Al alloy using V-welding groove at different angles (0°, 25°, 50°, 75°, and 90°) by Gas Tungsten Arc Welding (GTAW) method and examined the effect of welding groove angle on mechanical properties of the joints. In their study, they found that the weld groove angle had a significant influence on the mechanical properties and the highest tensile strength was obtained at 0^o welding groove angle. In their study, Ling et al. [13] joined JIS SS400 structural steel sheets in three different welding groove configurations and examined mechanical and microstructure properties of welded joints. In their study, the highest tensile strength was obtained in the joint made with a double half-rooted V-groove (K-groove) having 35^o welding groove angle and 2-mm root width. They determined the highest impact strength in half-V welding groove configuration with 35^o angle having a 9 mm root width.

In this study, the effect of different welding groove configurations on mechanical and metallurgical properties of the S275 structural steel joined by using the FCAW method was investigated. Tensile, bending and hardness tests were applied to determine the effect of welding groove configurations on mechanical properties of welded joints. In addition, the microstructures and grain morphology occurred in the weld metal and the heat affected zone (HAZ) which is under the effects of the weld metal and heat were evaluated.

2. EXPERIMENTAL

2.1. Materials

In this study, four different welding groove configurations were formed in a milling machine on the S275 construction steel sheets with sizes of 200×80×10 mm and joined with the FCAW method. Table 1 shows chemical compositions of S275 structural steel and welding wire, Table 2 shows their mechanical properties, and Figure 1 shows the microstructure image of the base metal.

Table 1. Chemical composition of the base metal and the welding wire (wt. %)

	C	Si	Mn	P	S
S275 structural steel	0.21	0.3	1.5	0.045	0.045
Rutile flux cored wire	0.04	0.6	1.4	0.015	0.015

Table 2. Mechanical properties of the base metal and the welding wire

	Yield Strength (MPa)	Tensile Strength (MPa)	% Elongation
S275 structural steel	min. 245	612	34
Rutile flux cored wire	420	500-640	min. 22

Table 3. Welding parameters

Welding current	Welding voltage	Wire speed	Welding speed	Gas flow rate
150 A	24 V	5 m·min^{-1}	5 mm·s^{-1}	12 lt·min^{-1}

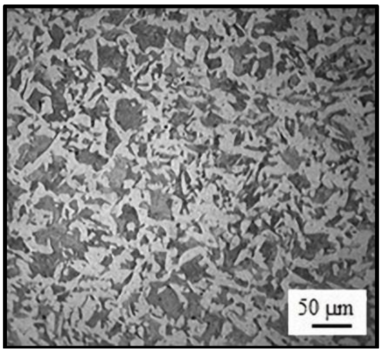

Figure 1. Microstructural image of the base metal

2.2. Methods

Welding grooves were opened on the steel sheets as seen in Figure 2 and they were centered by leaving a 1.2 mm root gap. The welded samples were coded as X_1 type, X_2 type, K_1 type and K_2 type. Mixed gas (Ar 86%, CO_2 12%, O_2 2%) was used as a shielding gas in welding processes. Rutile flux-cored wire (EN ISO 17632-A) with a diameter of 1.2 mm was used as the welding wire. In the production of welded samples, GKM 420-2W type gas metal arc welding machine was used. The welding processes were performed in the horizontal position by using the welding parameters in Table 3. Values of the welding parameters used in the study were decided as a result of the performed preliminary studies. The welding processes were carried out bidirectionally in two passes and they were left themselves to cool. Figure 3 shows the welded samples.

In addition to the metallographic tests, the joined samples were also subjected to mechanical tests such as hardness, tensile and bending tests. Three tensile samples, three bending samples, and one microstructure and hardness sample were prepared from welded samples. Tensile test samples were prepared according to ASTM-E8 standard. The bending test samples were produced according to TS EN ISO 5173 standard. Tensile tests were performed by using the BME-T series universal tensile tester with 100 kN capacity. Three-point bending tests were performed by using a 50 kN Instron 3369 tensile/bending tester at a test speed of 10 mm·min^{-1} and a 60-mm support opening. Grinding, polishing, and etching processes were applied to the microstructure and hardness samples by using standard methods. The samples were etched with a 2% nital solution and examined by using a Metkon Inverted Type metal optical microscope. Morever, the fracture surfaces of sample after tensile tests were examined by a scanning electron microscope (FEI Quanta FEG 250). The hardness distribution of the welded samples was determined in Rockwell B (HR_B) by using an universal hardness tester. The hardness processes were carried out with a 1/16" steel ball under a load of 100 kgf for 10 s and in 21 points with 2 mm intervals.

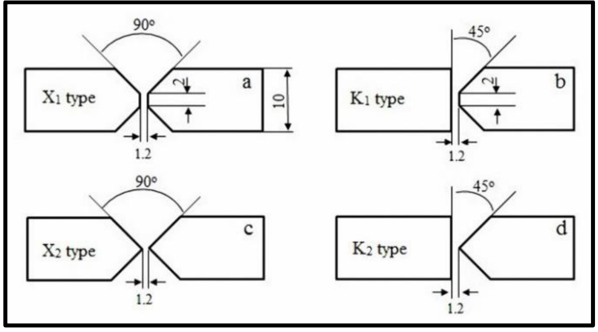

Figure 2. Welding groove configurations

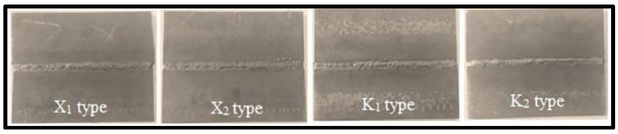

Figure 3. Images of welded samples

3. RESULTS AND DISCUSSION

3.1. Microstructure

Figure 1 shows the microstructure image of the base metal. When the microstructure of the base metal was examined, it was observed that it had generally coaxial grain structure. Figure 4 shows welding metal microstructures of the welded samples. The microstructure of the weld metal of all samples consisted of fine acicular grains. When the microstructures of the weld metal were examined, it could be determined that various structures such as acicular ferrite, ferrite, bainite and perlite occurred during solidification. Sönmez and Ceyhun [4], Ling et al., [13], and Kaya et al., [14] reported that grain boundary ferrite, widmanstatten ferrite, acicular ferrite, polygonal ferrite, bainite, and perlite may be present in the weld metal. Percentages of those phases changes depending on the cooling rate after the fusion welding of low carbon and low alloy steels.

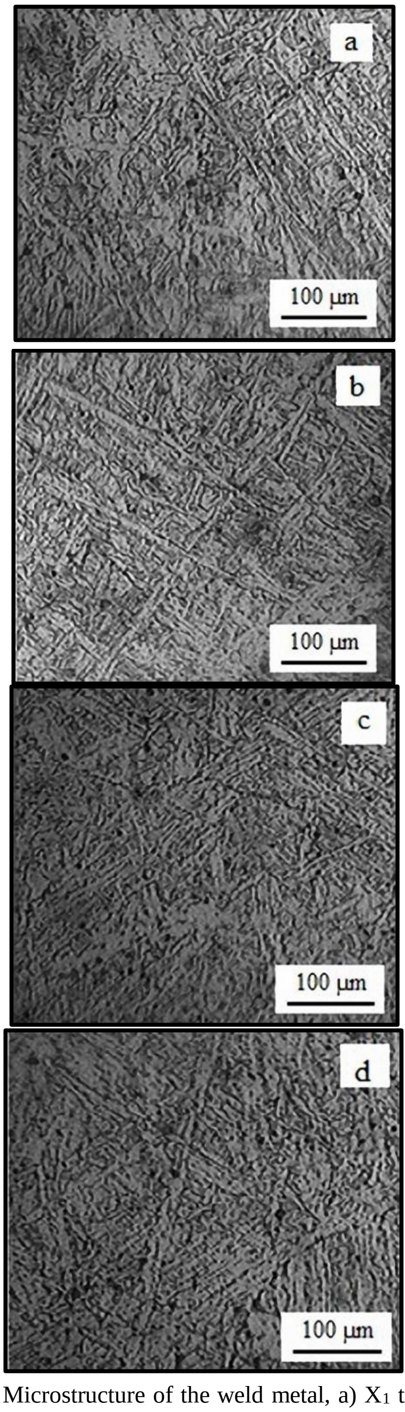

Figure 4. Microstructure of the weld metal, a) X_1 type, b) X_2 type, c) K_1 type, d) K_2 type

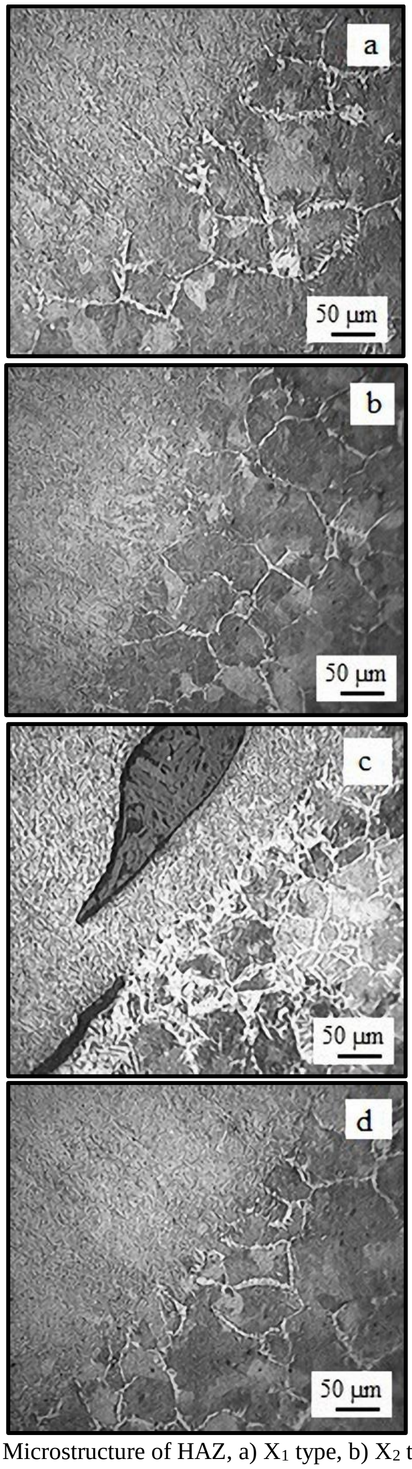

Figure 5. Microstructure of HAZ, a) X_1 type, b) X_2 type, c) K_1 type, d) K_2 type

Figure 5 shows microstructures of the heat affected zone (HAZ) of the welded samples. When the microstructures were examined, it was observed that various structures such as grain boundary ferrite and widmanstatten ferrite occurred during solidification in the weld metal and transition region. It was found that micro-void defect occurred in the weld metal in joint with K_1 type welding groove configuration. In addition, a joint defect (insufficient penetration) were occurred in the weld metal-HAZ transition zone of the same sample. Grain coarsenings occurred at HAZ in all samples. Kaya et al., [14] and Durgutlu et al., [15] stated that coarse grains formed with the effect of heat input in the zones nearest to the weld metal in the arc welding methods.

3.2. Hardness Mesurements

Figure 6 shows the hardness distribution of the weld zone (base metal, HAZ, weld metal) of the samples joined in different welding groove configurations by using the FCAW method. In welded samples, the highest hardness values were measured in the weld metals, which was followed by HAZ and base metal, respectively. The mean hardness of the base metal was determined as ~84 HR_B. When the mean hardness values of the weld metal were compared, it was found as 95 HR_B in X_1 sample, 95 HR_B in X_2 sample, 98 HR_B in K_1 sample, and 99 HR_B in K_2. According to the obtained results, the welding groove form affected the weld metal hardness. When the hardness values of the welded samples measured in HAZ were compared, they were obtained as 95 HR_B in X_1 sample, 92 HR_B in X_2 sample, 92 HR_B in K_1 sample, and 93 HR_B in K_2 sample. The fact that the hardness values measured from different regions were close to each other is thought to be caused by the fact that the temperature and welding parameters between passes were appropriately selected and were under control [3]. Kaya et al., [14] stated that the hardest zone was the weld metal in the joining of steels with carbon content less than 0.22% via arc welding and the hardness values decreased from the weld metal to the base metal. Similarly, in the study conducted by and Kılınçer and Kahraman [16], Aksöz et al., [17] through arc welding they reported that the highest hardness values in the weld zone were obtained in the weld metal, which was followed by HAZ and base metal, respectively. In the literature [14-18], the hardness is recommended not to exceed 350 HV (~ 109 HR_B) as a measure against cracking in HAZ in welding of low-carbon low alloy steels. Hardness distributions of welded samples were observed to be below this critical value. In the macro and micro examinations made on welded samples, no crack defect was found in the weld seams and weld zone.

3.3. Tensile Strength

Figure 7 shows the tensile test results of the samples joined with different welding groove configurations by using the FCAW method. As a result of the tensile test, it was found that the tensile strength of the base metal was 612 MPa and the % elongation was 34%, and it fractured near to clutch part of the base metal. When the tensile test results obtained from welded joints were compared, the highest tensile strength was obtained from the welded samples joined with X_2 welding groove configuration. 589 MPa tensile strength was obtained in the sample joined with the X_2 welding groove configuration. When the tensile strength performance of this sample was compared with the base metal, a decrease of 3.8% was observed.

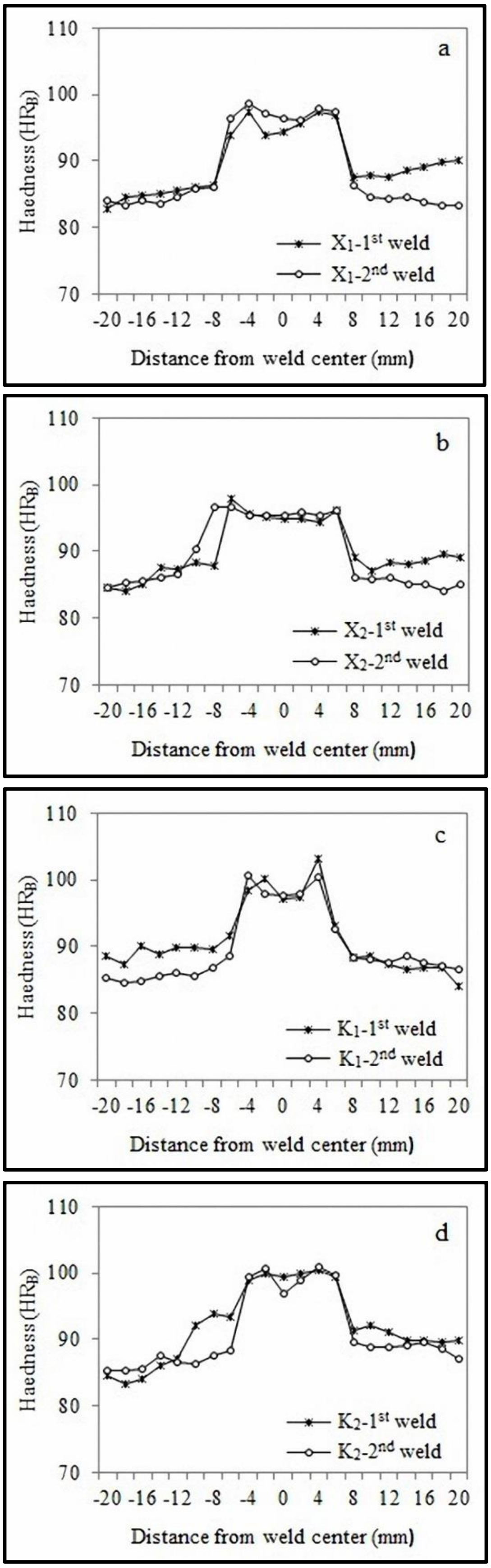

Figure 6. Hardness distribution of the welded samples, a)X_1 type, b) X_2 type, c) K_1 type, d) K_2 type

When the % elongation of the sample joined with the X_2 welding groove configuration was compared with % elongation of the base metal, a decrease of 9.7% was observed. In the tensile strengths of the welded samples joined with the K_2 and X_1 welding groove configurations, decreases of 12.4% and 14.2% occurred, respectively. When the % elongations of these samples were compared, it was determined that while there was a decrease of 19.7% in the sample joined with K_2 welding groove configuration, this decrease was 14.2% in X_1 welding groove configuration. The lowest tensile strength was obtained in the joint made by the K_1 welding groove configuration and in this sample the tensile strength performance value reduced at the rate of 30.7% compared to the base metal and was 424 MPa. When the % elongation amount of the sample joined with the K_1 welding groove configuration was compared with the % elongation amount of the base metal, a decrease of 38.2% occurred. Fracture behavior of welded samples occurred in ductile style. In addition, the fracture surfaces of the welded samples was observed that the microporosity. The decrease of tensile properties was caused by micro defects in the weld seam (Fig. 8). Kaya et al., [14] stated that the first property sought in the welded joints should have the strength of joint to be the same as or close to that of the base metal. In the study, it was determined that the welding groove configuration was effective in the tensile strength of the welded samples and the tensile strength nearest to the base metal was obtained in the joint performed with the X_2 welding groove configuration. İpek and Elaldi [11] stated that the welding groove geometry and angle were effective on the tensile strength of the high-strength armor steel joined with the GMAW method and they obtained the highest tensile strength in the V-welding groove geometry at the welding angle of 54^{o} in their study. The fracture occurring in the welded samples as a result of the tensile test was usually associated with the base metal-weld metal transition zone. HAZ and weld metal-base metal transition zone are the most critical region of welded joints.

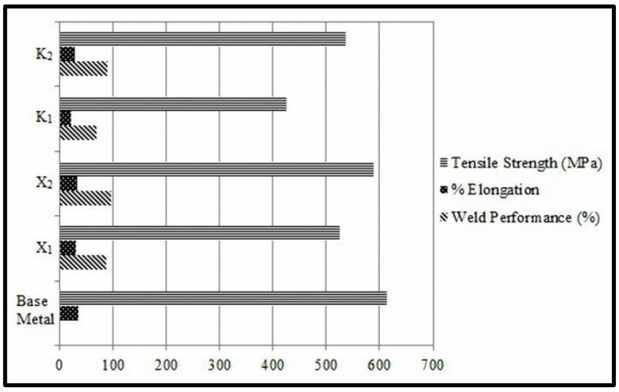

Figure 7. Tensile test properties of the welded samples.

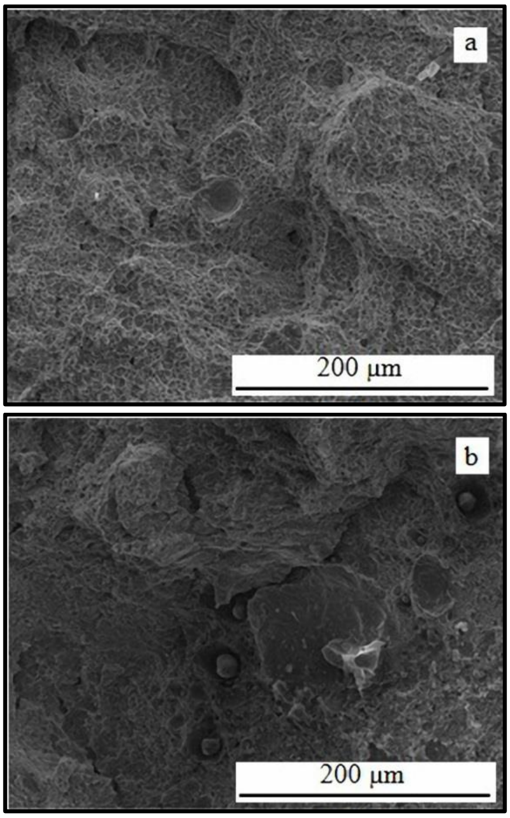

Figure 8. Fracture behaviour of the welded samples, a) X_2, b) K_1

3.4. Bending Strength

Figure 9 shows the bending test results of the welded samples joined with the base metal and different welding groove configurations. When the bending test results were examined, the maximum bending strength of the base metal was determined to be 1247 MPa. The bending strength of the welded samples was found to be lower than the base metal. When the bending test results obtained from the welded joints were compared, the highest bending strength was obtained from weldments prepared with X_2 type welding configuration. In a sample joined with such welding groove configuration, a bending strength of 1068 MPa was obtained. When the bending strength performance of this sample was compared with the base metal, a decrease of 14.3% was determined. Decreases of 20% and 23.6% were determined in the bending strengths of the welded samples joined with the X_1 and K_2 type welding configurations, respectively. The lowest bending strength was obtained in the joint made with the K_1 type welding configuration. The bending strength performance of the sample joined with this type of welding groove configuration decreased by 30% compared to the base metal and was determined as 874 MPa. In the bending test results, it was observed that fractures occurred in all samples. In all welded samples, the fracture occurred mainly near to the base metal-welding metal transition zone.

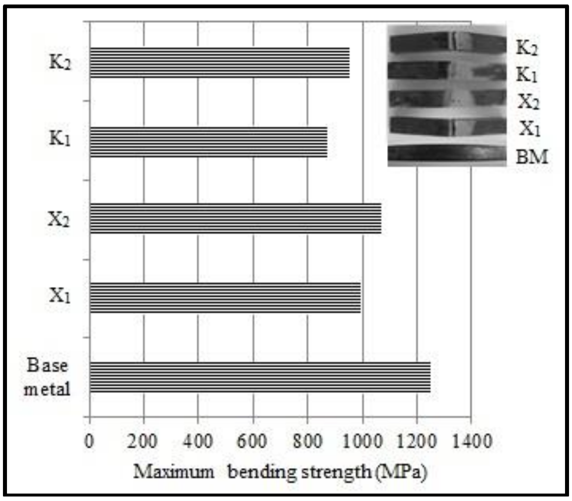

Figure 9. Bending test properties of welded weldments.

4. CONCLUSION

The S275 structural steel sheets were joined in different welding groove configurations by using FCAW method and the microstructure and mechanical properties of the welded joints were investigated and the results obtained are summarized below.

1. The study firtstly shows that due to fact that various stresses such as tensile, compression, bending, etc might be occured on most steel constructions during welding joint, chosing and determineation the most appropriate welding groove configuration is very inportant.
2. Experimental results show that welding groove configuration has great influence on the mechanical and microstructure properties of the weldments.
3. As a result of microstructure studies, it is seen that different structures such as ferrite, widmanstatten ferrite, and acicular ferrite were formed in the weld metal and coarse-grained region.
4. It is observed that hardness of the weld metal was higher than HAZ and base metal in all joints.
5. Some defects were seen in the weldments with K_1 type welding groove configuration causing to obtained lower values of mechanical properties.
6. The highest tensile and bending strengths were obtained from the welded samples with X_2 type welding groove configuration.

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