Journal of Naval Sciences and Engineering
2020, Vol. 16, No.2, pp. 171-192
Mechanical Engineering/Makine Mühendisliği

RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

INVESTIGATION OF MECHANICAL PROPERTIES OF WELDING ELECTRODES USED FOR HIGH STRENGTH LOW ALLOY STEELS*

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Date of Receive: 24.08.2020 **Date of Acceptance: 26.09.2020**

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ABSTRACT

In this study, GeKa Tempo B65 electrodes are used in the welding of high strength low alloy (HSLA) S355JR steel. It is aimed to increase the impact resistance of the electrodes at minus temperatures. In order to observe the mechanical properties of the materials, tensile, impact energy test and CTOD test are performed. Implicit electric arc welding is chosen as the welding method. Electrodes with three different compositions and grain structures are prepared for welding. Optical microscope is used to observe the surface images of the weld seams. It is observed that the grain structure of the sample, the amount of alloying elements and the heat input during the welding of the sample significantly affect the impact resistance of the welded samples.

Keywords: *High Strength Low Alloy Steel, Electrode Materials, Welding, Mechanical Properties, Microstructure.*

YÜKSEK MUKAVEMETLİ DÜŞÜK ALAŞIMLI ÇELİKLER İÇİN KULLANILAN KAYNAK ELEKTRODLARININ MEKANİK ÖZELLİKLERİNİN İNCELENMESİ

ÖZ

Bu çalışmada GeKa Tempo B65 elektrotları yüksek mukavemetli düşük alaşımlı (HSLA) S355JR çeliğinin kaynağında kullanılmıştır. Eksi sıcaklıklarda elektrotların darbe dayanımının arttırılması amaçlanmaktadır. Malzemelerin mekanik özelliklerini incelemek için çekme, çentik darbe testi ve CTOD testi yapılmıştır. Kaynak yöntemi olarak örtülü elektrik ark kaynağı seçilmiştir. Üç farklı bileşime ve tane yapısına sahip elektrotlar kaynak için hazırlanmıştır. Kaynak dikişlerinin yüzey görüntülerini gözlemlemek için optik mikroskop kullanılmıştır. Numunenin tane yapısının, alaşım elementlerinin miktarının ve numunenin kaynağı sırasındaki ısı girişinin, kaynaklı numunelerin darbe dayanımlarını önemli ölçüde etkilediği görülmüştür.

Anahtar Kelimeler: *Yüksek Mukavemetli Düşük Alaşımlı Çelik, Elektrot Malzemeler, Kaynak, Mekanik Özellikler, Mikroyapı.*

1. INTRODUCTION

High strength low alloy steels (HSLA) are widely used for the production of welded metal structures in various areas of the modern industry, including construction, agriculture, transportation, engineering and defence. These steels have a ferritic-pearlitic or ferritic-bainitic structure. There are some parameters that determine the quality of the weld seam and its connection. Before the welding process, many factors such as material properties should be reviewed. In melting based welding methods, it is mandatory to protect the welding area with auxiliary materials. Appropriate selection of these parameters simplifies working conditions and increases the probability of obtaining the required welding connection (Badkoobeh et al., 2020; Pathak et al., 2020; Berdnikova et al., 2009; Antonini, 2014).

The process of selecting a specific arc welding depends on many factors, including the thickness and type of the base metal, the size and strength of the desired weld, the welding speed or volume, the cost, the location of the material (e.g. vertical or horizontal). Among the covered electrodes used in the electric arc welding method are acidic, cellulosic, oxide covered, basic and rutile electrodes. Electrode selection is made during the design of the welding connection and there is no perfect electrode that can be used in all areas. The electrode that is most suitable for a particular aim is selected by considering a number of factors, especially the type and mechanical properties of the steel. Basic electrodes coated with calcium fluoride are widely used in arc welding. Basic electrodes can be used in any welding position. It gives very good welding seams even at the welding of the components below 0˚C. For a good weld seam, basic electrodes should be kept at right angles as far as possible in the welding direction. Basic electrodes are not prone to hot and cold cracking (Ragu et al., 2015; Sjörgen et al., 1984; Oğuz, 1989).

Basic electrodes are manufactured with thick covering. Although they are packed in airtight boxes, they should not be left in damp places for a long time. Due to the moisture, hydrogen embrittlement may occur in the electrodes during welding. Hydrogen embrittlement is not noticeable during welding. It occurs after a certain amount of time, and it is a major problem for the material (Erofeev et al., 2019; Anık et al., 1991). Basic electrodes are subjected to drying at approximately 500°C to prevent this situation. The electrodes used in Russia or Ukraine have high refractive impact energy at minus temperatures. Therefore, there are many parameters to increase the toughness of basic electrodes used at minus temperatures. Some of these are the reduction of grain size, transition temperature and the effect of alloying elements. The alloying elements such as Ni, Cr, and Mo control the ferrite/austenite balance and the mechanical properties. The phase balance and mechanical properties are also influenced by the heat input and cooling rate during welding (Atia et al.,1991).

In order to observe the mechanical properties of the materials, tensile and impact energy tests are performed. The tensile test is a mechanical test performed by applying a longitudinal or axial load at a given elongation rate to a stretching sample sized to predetermined standards (Khayal, 2019). The impact energy test is carried out to examine the mechanical properties of the metals, especially in conditions suitable for brittle breakage and to determine the amount of impact resistance required to break the sample under a force. After the impact test, a material may also have a fracture resistance (Pettarin et al., 2003; Khan et al., 2020). Small grain steels have better yield and tensile strength than coarse grain. The differences between the weld metal and the impact strength of the base metal may seem insignificant, but the fracture toughness of a weld metal may be significantly lower or greater than that of the base metal (Tuma et al., 2006). Fatigue CTOD test method has been developed to easily determine the minimum CTOD value in welded connections. In other words, the "Crack Tip Aperture" test is one of the most common parameters used in the industry. Because the tests are practical and the methods are standardized. The CTOD test successfully analyzes every phase of crack in elasto-plastic fracture mechanics (Ishikawa et al., 1984; Avila et al., 2016; Ay, 1995).

In this study, it is aimed to increase the impact energy of basic electrodes used in the welding of high strength low carbon steels used at minus temperatures and investigation with CTOD test has been done.

2. MATERIALS AND METHODS

In this study, S355JR steel was joined to the S355JR by using GeKa Tempo B65 basic electrode with butt welding method. DC (+) was used in the welding. S355JR steel had a size of 20 mm x 180 mm x 400 mm.

The code of S355JR steel was made according to TS EN 10025-2: 2006 quality standard. The number "355" in this code represented the yield strength of the steel. The JR code represented the impact energy at +20 ˚C. The impact energy of S355 steel at 20˚C was 27 J. The chemical composition of S355JR was given in Table 1.

Table 1. The chemical composition of S355JR steel.

Steel	%C max	%Si max	%Mn max	%P max	%S max	%Cu max	%N max	%Other
S355JR	0.24	0.55	1.60	0.04	0.04	0.4	0.012	97.11

The composition of the weld metal was given in Table 2 and the mechanical properties of the weld metal were given in Table 3.

Table 2. The composition of the weld metal (S355JR).

%C	%Si	%Mn	%Ni	%Mo	%Other
0.06	0.3	1.2	0.8	0.35	97.29

Table 3. The mechanical properties of the welding metal (S355JR).

Yield Strength (MPa)	Tensile Strength (MPa)	% Elongation (L_0=5d_0)	Impact Energy (-60˚C)(MPa)
Min. 550	630-750	Min. 22	Min. 47

A total of 10 rows of weldings were made for each electrode. The welding speed, amper and voltage were observed to calculate the heat inputs of each pass. The welded material was shown in Figure 1. The preheating temperature of the electrodes was 80˚C and the temperature between passes was 130ºC.

Figure 1. Welded S355JR and weld seam.

Three different electrodes were used for welding processes. These electrodes were; 6356, 6357, and 6360. Si was added into 6356 coded electrodes. The amount of Si was reduced in the 6357 coded electrodes. Ti was added into the 6360 coded electrodes to decrease the grain size. GeKa Tempo B65 basic electrode had a size of 320 mm x 350 mm.

Since the basic electrodes had a hygroscopic structure, they were subjected to heating before being used in the welding process. After being kept at 250 ºC for 2 hours, they were stored at different temperatures in ovens according to their chemical structure. The chemical composition of the samples welded with GeKa Tempo B65 electrode was given in Table 4.

Table 4. The chemical composition of the samples welded with GeKa Tempo B 65 electrode.

Electrode	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%Cu	%Ti	%V	%Al
6357	0.065	0.447	1.3	0.01	0.05	0.035	0.96	0.192	0.065	0.008	0.017	0.001
6360	0.067	0.477	1.511	0.026	0.012	0.035	0.864	0.214	0.030	0.014	0.021	0.004
6356	0.078	0.63	1.45	0.019	0.007	0.047	0.96	0.2	0.057	0.011	0.017	0.004

The tensile test was performed using Zwick / Roell Z600 tensile device. The impact test was performed by using a Zwick / Roell RKP300 impact test device, controlled by a thermometer. In order to observe the impact resistance of the samples at minus temperatures, dry ice was taken from the CO_2 tubes and placed in a metal container together with the samples. The test (ASTM E23 impact test) was done at -60˚C temperature. CTOD (Crack Tip Opening Displacement) test samples (Figure 2) were prepared according to the ISO 15653 CTOD test standard.

Figure 2. CTOD test sample.

3. RESULTS AND DISCUSSION

The welding efficiency of the covered electrode arc welding was taken as 0.8 (ŋ) with reference to the TS EN 1011-1: 2010 standard. The formulation of the heat input was given in (3.1). Heat inputs of the samples welded with electric arc welding were shown in Table 5, 6 and 7.

$$Q = \frac{ŋ\ x\ I\ x\ V\ x\ t}{S\ x\ 1000} \quad \textbf{(1)}$$

Q: Heat input (J / mm)
ŋ: Welding efficiency
I: Current (A)
V: Voltage (V)
t: Welding time (seconds)
S: Length of the welding piece (mm)

Table 5. Heat input values of the sample with code 6357.

Line	Amper (A)	Voltage (V)	Welding Time (Seconds)	Heat Input (J/mm)
1	134	34.7	143	1.329
2	132	34.4	113	1.025
3	131	34.4	130	1.117
4	131	34.7	124	1.127
5	130	34	122	1.348
6	130	34.4	127	1.078
7	130	34	134	1.184
8	129	34.7	138	1.235
9	128	33.7	120	1.035
10	128	33.2	93	0.790

Table 6. Heat input values of the sample with code 6360.

Line	Amper (A)	Voltage (V)	Welding Time (Seconds)	Heat Input (J/mm)
1	132	37	123	1.200
2	133	35	110	1.024
3	130	34	125	1.104
4	131	34	134	1.193
5	131	34	132	1.175
6	131	35	127	1.164
7	129	34	134	1.174
8	129	35	138	1.245
9	129	33	115	0.978
10	128	33	68	0.565

Table 7. Heat input values of the sample with code 6356.

Line	Amper (A)	Voltage (V)	Welding Time (Seconds)	Heat Input (J/mm)
1	129	35	113	1.020
2	126	34	113	0.968
3	122	34	118	0.978
4	122	33	111	0.949
5	132	34	118	1.058
6	131	34	125	1.112
7	132	33	125	1.088
8	131	33	121	1.045
9	132	33	119	1.036
10	126	33	65	0.54

The mechanical properties of the samples welded with GeKa Tempo B65 electrodes were given in Table 8.

Table 8. The mechanical properties of the samples welded with GeKa Tempo B65 electrodes.

Electrode Codes	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**% Elongation**	**Impact Energy (-60^{0}C) (J)**
6357	619	679	23	79 (±8)
6360	640	706	22	63 (±7)
6356	656	722	22	62 (±7)

According to Table 8; while the yield and tensile strength values of the electrode coded of 6357, in which the Si amount was reduced, were the lowest, the impact resistance value at -60^{0}C was the highest. The electrode coded 6357 had a graphite structure. Among the important details in welding seams were the heat input entering the welding zone and welding swing. Considering these factors, the heat input values of the 6357 coded electrodes were much better than 6360 and 6356 coded electrodes.

Ti was added as a grain thinning element to 6360 coded electrodes. The tensile and yield strength of the sample increased as the grain sizes of the materials became thinner. However, it could be seen that while the tensile and yield strength increased, there was a decrease in the elongation and impact resistance values. The % elongation was 23 mm in the 6357 coded electrode and the % elongation was 22 mm in the 6360 coded electrodes. The impact energies of 6357, 6360, and 6356 coded electrodes were 79J, 63J, 62J, respectively.

It was aimed to determine the effect of Si exactly on the welding seam in the electrode with 6356 code. 0.19% Si was added to 6357 coded electrodes. Considering the results, it was observed that there were not obvious differences in the results between 6356 coded samples and Ti added 6360 coded samples. The yield and tensile strengths were different in the 6356 coded samples with an increased Si and Ti as a grain thinner. For samples with Ti added 6360 coded and with Si increased 6356 coded, yield strength increased from 640 MPa to 656 MPa and tensile strength increased from 706 MPa to 722 MPa. The elongation and impact resistance values were almost the same.

The tensile and yield strength of the samples welded with GeKa Tempo B 65 electrode was shown in Figure 3. The impact energy of the welded samples with GeKa Tempo B 65 electrode was shown in Figure 4.

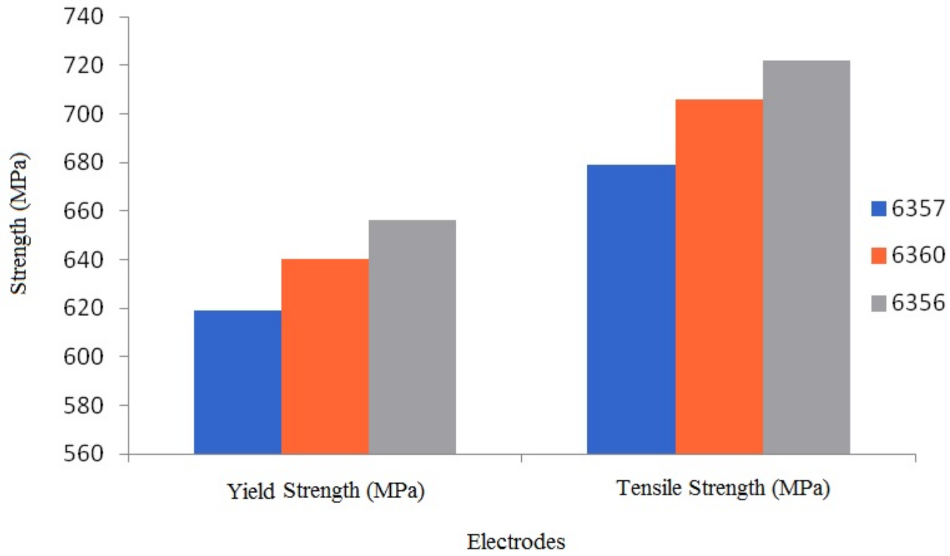

Figure 3. The tensile and yield strengths of the samples welded with GeKa Tempo B65 electrode.

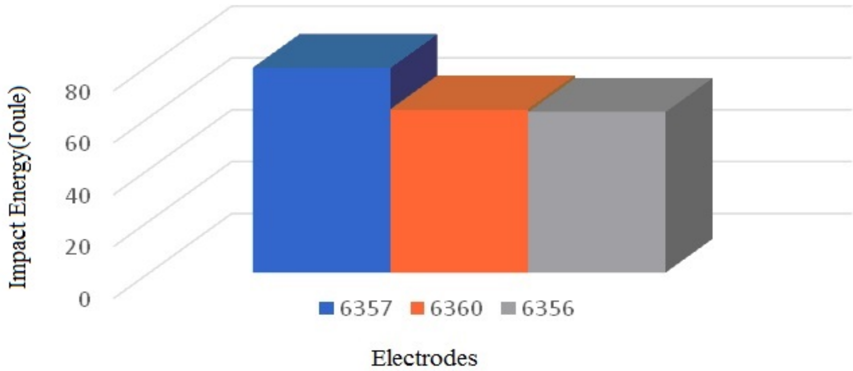

Figure 4. The impact energy of the welded samples with GeKa Tempo B 65 electrode.

When the fracture surfaces of the samples were examined as a result of the impact tests, it was observed that the three samples were not brittle. The fracture surfaces of the samples welded with different electrodes after notch impact test were shown in Figure 5.

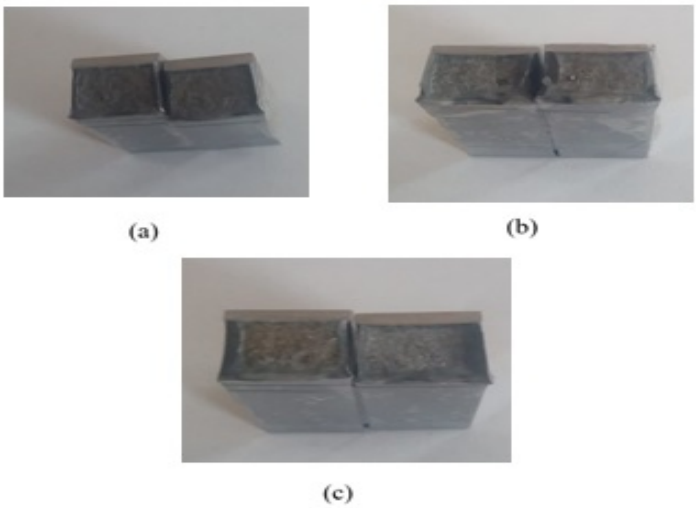

Figure 5. The fracture surfaces of the samples after impact test welded with (a) 6356, (b) 6357, and (c) 6360 coded electrode.

CTOD test was performed at -10˚C according to ISO 15653 standard. The macro photographs of three electrodes before CTOD test were given in Figure 6.

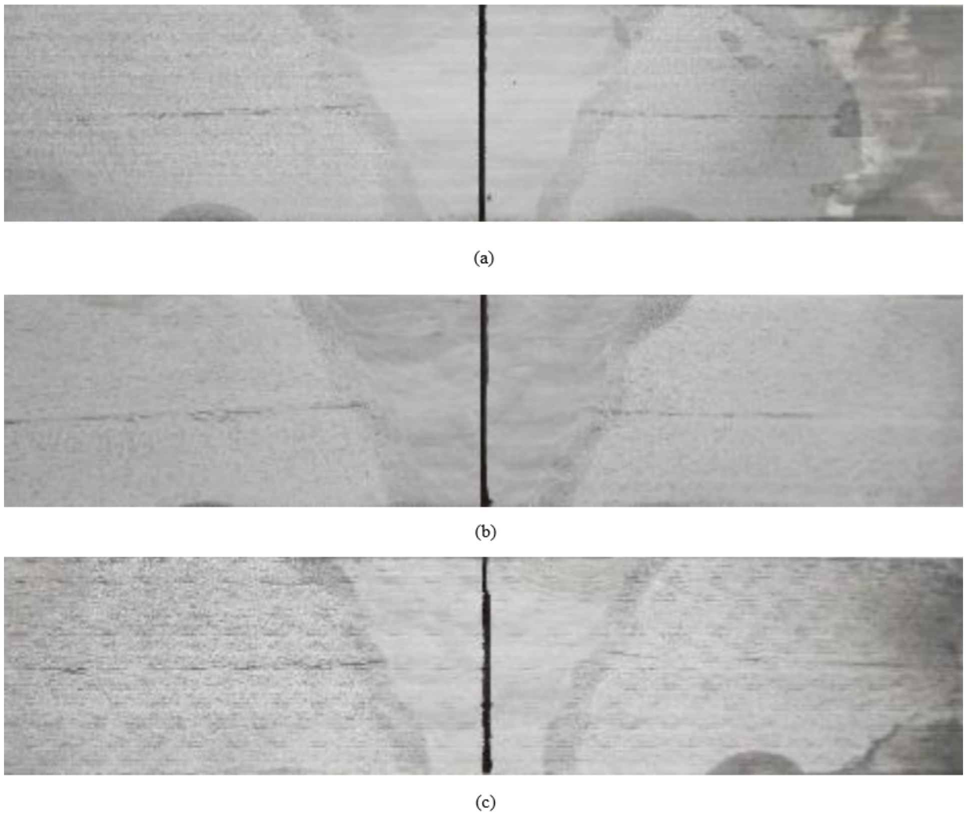

Figure 6. The macro photographs of a) 6356, b) 6357, and c) 6360 coded electrodes before CTOD test.

As seen from Figure 6, it was observed that the welding area of 6356 coded electrode and the HAZ (heat affected zone) was very narrow because of the low heat input values during welding. Heat input values were given in Table 7. It was observed that the welding zone of 6357 coded electrode and the HAZ were quite large because of the high heat input values during welding. It was also observed that the welding area of the 6360-code electrode, in which Ti was added as a thinner, and the HAZ were at a medium level. The reason was the medium level of heat input values at the welding of the 6360 coded electrodes.

CTOD test values were given in Table 9. The test conditions of the electrodes were given in Table 10. CTOD test results and crack length measurements were shown in Table 11.

Table 9. CTOD Test Values.

Yield Strength at Room Temperature (MPa)	550	**Yield Strength at Test Temperature (MPa)**	572
Tensile Strength at Room Temperature (MPa)	630	**Tensile Strength at Test Temperature (MPa)**	656
Support Distance (mm)	64	**Sample Type**	SENB
Front Crack Temperature	Room Temperature	**Front Crack Last Load (N)**	4750
Blade Type	Integral	**Blade Thickness (mm)**	0
Test Speed (mm/min)	1.50	**Displacement Control**	Displacement

Table 10. Test conditions of the electrodes.

	6356	6357	6360
Crack Order Position	NP	NP	NP
Notch Position	Welding Zone	Welding Zone	Welding Zone
Thickness (mm)	15.90	15.87	15.89
Width (mm)	15.98	16.00	15.98
Dimensional Control	Acceptable	Acceptable	Acceptable

CTOD test results and crack length measurements were shown in Table 11.

Table 11. CTOD test results and crack length measurements.

	6356	6357	6360
Machined Notch Length (mm)	5.50	5.50	5.50
First Crack Front Length (mm)	8.09	7.98	8.24
Front Crack Length (mm)	2.59	2.48	2.74
First Relative Crack Length (a0/W)	0.51	0.50	0.52
Validity	Acceptable	Acceptable	Acceptable
Last Crack Front Length (mm)	8.61	8.52	8.77
Average Crack Elongation (mm)	0.51	0.54	0.54
Fracture Type (C,U,M)	M	M	M
Extensometer Displacement (mm)	0.97	1.14	1.01
Load at CTOD Value (kN)	15.89	16.34	15.30
CTOD Value (mm)	0.299	0.355	0.303

According to the results, the best CTOD value was observed in the 6357 coded electrodes, in which the Si amount was reduced. It had also the highest impact resistance. CTOD test allowed to see the breaking mechanism of the material and determine the resistance of the material to the crack progress. The test was carried out by examining the progress of the crack as a result of the notch previously opened on the test sample, a measuring device connected to this notch and the bending was done. During the test, the crack behavior was observed. The main purpose of the test was not to see whether the material cracked against a particular load, but how long it took for it to be critical after the crack is detected. The fracture values of all three electrodes calculated against extensometer displacement (mm) against the applied load (kN) in the CTOD test were shown in Figure 7.

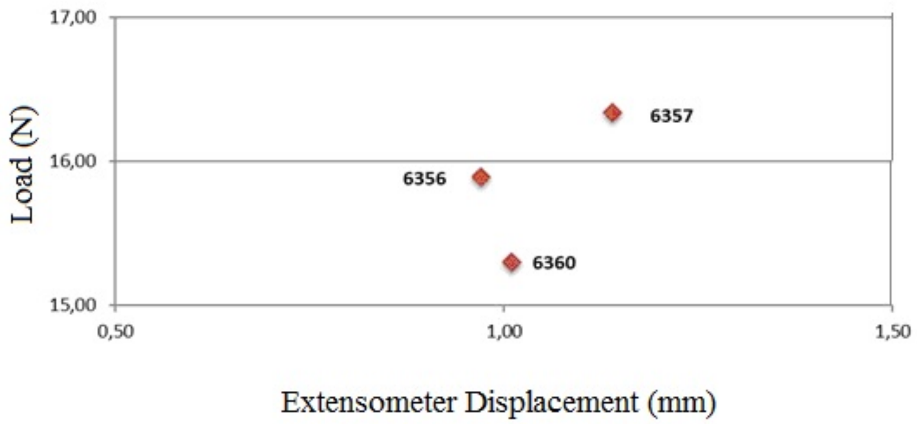

Figure 7. The fracture values of three electrodes in CTOD test.

When the test results of CTOD test sample of 6356 coded electrodes (with the increasing the amount of Si), the first crack length was 8.09 mm and the last crack length was 8.61. The average crack elongation was 0.51 mm. In CTOD test, while the load applied to the electrode sample with the increasing the amount of Si was 15.89 kN, the extensometer displacement of the sample was 0.97 mm. The first crack length of 6357 coded electrode was 7.98 mm, the last crack length was 8.52 mm. The average crack elongation was 0.54 mm. The load applied to electrode was 16.34 kN, while the extensometer displacement of the sample was 1.14 mm.

The first crack length of 6360 coded electrode which had a fine grain structure with the addition of Ti, was 8.24 mm and the last crack length was 8.77 mm. The average crack elongation was 0.54 mm. The load applied to electrode the was 15.30 kN, the extensometer displacement of the sample was 1.01 mm.

4. CONCLUSION

In this study, the increase of the impact energy of basic electrodes used in welding of high strength low carbon steels used at minus temperatures and their investigation with CTOD test had been done. While the grain size of the material and the amount of Si increased, it was observed that high strength low alloy steels only had a positive effect on the yield and tensile strengths of the welding material, but it had a negative effect on impact resistance. If all the electrodes are compared together; the electrode coded 6357 had the highest impact energy (79 J). The impact energy of the 6360 coded electrodes was 63 J, and the impact energy of the electrode coded 6356 was 62 J. Because of the thermal cycles, Si addition and grain thinning had a negative effect on impact resistances. The welding time was determined due to the amount of ampere and voltage used during welding, and the heat input was an important parameter in this regard. Heat input and output were important for the strength of the weld seam. When we examined the fracture surfaces of all three electrodes after notch impact test, it was observed that the three electrodes had not a brittle fracture. Since the welding should be done with the least amount of energy, it was desired to have the lowest level of heat input during welding. The heat input values were low in the electrode coded 6356, in which the Si amount was increased. When macro photos were examined before CTOD test, it was observed that heat affected zone (HAZ) was very narrow in the electrode coded 6356, in which the Si amount was increased. Because of the high heat input values, the HAZ was wide in the electrode coded 6357, in which the Si amount was decreased. The HAZ had a medium width in the electrode coded 6360, in which Ti was added as a thinner. The heat input had also medium level in the electrode coded 6360. The electrode coded 6357, which had a reduced Si amount, had the best toughness value. The average crack elongation values of the 6360(a fine grain structure with the addition of Ti) and 6357(the amount of Si was reduced) coded electrodes were the same. The amount of energy required to break the 6360 coded electrodes was lower than the amount of energy required to break the 6357 coded electrodes. The 6357 coded electrodes with a reduced Si amount had the highest impact resistance and also the highest CTOD value.

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