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Research Paper

Correlation between the Weld Residual Stresses and its Tensile and Impact Strength

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Abstract. In this study, the tensile strength, impact strength, and the hardness of the weld are determined. A criterion is proposed for describing the effect of residual stress on the weld mechanical properties. Dimensionless parameters such as R_{ya} (the average of residual stress over the material yield strength), R_{ym} (the maximum residual stress over the material yield strength), R_{u2} (the difference in the residual stress over the material ultimate strength), and R_{u3} (the difference ratio between the maximum and minimum of three-dimensional residual stresses over the material ultimate strength) are presented to describe the influence of residual stresses on the actual mechanical behavior of the welded pipe. Maximum R_{ya} criterion and lowest strength are obtained at the weld gap center on the external surface of the pipe. The sharp decline in R_{u2} criteria is consistent with the severe reduction in impact strength perpendicular to the weld gap.

Keywords: Assembling, Residual stress, Girth welding, Mechanical properties, Dimensionless parameters.

1. Introduction

The welding takes about 25 percent of the time creating a new transmission pipeline [1]. In general, residual stresses are divided into two groups (i.e. microscopic and macroscopic). The resource of these stresses is very diverse and can be categorized into three main sets of mechanical, thermal, and metallurgical [2]. Metallurgical residual stresses are often microscopic residual stress, but mechanical and thermal residual stresses are considered to be of the macroscopic kind. Creation and distribution of microscopic residual stresses in the body much depends on the processing of raw materials and often are available in all materials in a scattered form [3]. Empty places, displaced atoms and crystal defects caused by deformation and faults of grain boundaries are major risk factors for these types of stresses. In the macroscopic scale, a group of grains or a part of the under stress pieces are located. Macroscopic stresses caused heterogeneity in the mechanical behavior of various parts [4]. In summary, we can consider local and non-uniform heating factors, temperature deforming, the temperature dependence of steel yield stress, degrees of temperature inhibition and mechanical constraints as the most important factors that bring about weld residual stresses [5]. During welding, the high heat flux from the electric arc causes the creation of non-uniform temperature in the weld zone. After cooling completely, residual stresses of welding zone are tensional and may be yield strength in the base metal [6]. The level of these stresses in the heat affected zone (HAZ) with increasing the distance from the weld center is tended forward the formation of compressive stresses in order to balance the tensile stresses [7]. Investigation of behavior during service gas pipeline in the zone of large residual stresses due to welding process is required to identify the distribution of these stresses. The hole drilling as a semi-destructive method with the application range of approximately 22% is the most common method of measuring residual stresses and is used for determining residual stresses near the surface [8]. This method involves the installation of the strain gauges, creating a hole near the strain gauges and measuring the released strain [9]. Buchard et al. measured hoop residual stresses in austenitic stainless steel pipe with a thickness of 432 mm and a diameter of 63.5 mm. The experimental results of the neutron diffraction experiment and hole drilling had a perfect match [10]. Law et al. evaluated girth welding residual stresses of steel X-70 with a diameter of 275mm and three different thicknesses (5.4, 6.4, 7.1 mm) using neutron diffraction. Results show that the maximum residual stress occurs in thinner pipes [11]. Silva et al. studied girth welding residual stresses by the method of shielded metal arc welding in carbon steel with a diameter of 1016 mm and the thickness of 66 mm using X-ray diffraction. They concluded that the girth welding residual stresses are different even at the same laboratory condition [12]. Sattari-far and Farahani examined the shape effect and pass number in the girth welding of austenitic stainless steel with a diameter of 320 mm and the thickness of 10 mm. The experimental results and simulation showed a proper match [13]. Rubin et al. evaluated the residual stresses using X-ray diffraction in X70 pipelines with a diameter of 1016 mm and the thickness of 26.2 mm [14]. The amounts of the residual stress of two methods used in their study indicated that the maximum residual stresses happen in parallel to the heat affected zone of welded side. Paddea et al. examined the girth welding residual stresses of ferritic-martensitic pipe with grade P91 by neutron diffraction testing [15]. The results showed that the maximum tensile residual stresses happened in the interface of the weld and heat affected zone. Obeid et al. evaluated parameters of thermal and residual stress and effect of the welding process in lined pipe recently [16-17].

In this paper, finding an empirical relation between the microstructure and mechanical properties of the girth weld of X70 steel pipe is considered. To assess the actual effect of residual stresses on the static and dynamic behavior of this welded pipe, a new criterion is also proposed.

2. Specimen Preparation

Welding on two pieces of 50 cm API X70 spiral steel pipe with a diameter of 1422 mm and the thickness of 19.8 mm is done based on the standard in 9 passes. These passes include root pass, hot, filling and cap passes, and the process was done respectively, with three electrode diameters of 3.2, 4, 5 from the root to the cap using SMAW process. Figure 1 shows the welding process [18-19].

Fig. 1. Girth welding of the pipe.

3. Experimental Results

3.1. Residual stress distribution

Hole drilling test was done in the HAZ on the external surface of the pipe at intervals of 4, 10, 22, 43, 75 mm from the weld centerline. At the inner surface of the pipe, rosettes are located at 3 points of weld centerline and heat affected zone at distances of 22 and 55 mm away from the weld center. The tests were conducted according to ASTM E837 standard [20]. Figure 2 displays the evaluation points of residual stresses on the internal and external surfaces of the pipe. Table 1 and 2 indicate the axial and circumferential residual stresses on the external and internal surfaces of the pipe.

Fig. 2. Residual stresses on the external surface of the pipe.

Table 1. Residual stresses on the external surface of the pipe.

Distance From Weld Centerline (mm)	Axial Residual Stresses (N/mm^2)	Hoop Residual Stresses (N/mm^2)
0	-68	318
8	-4	217
19	96	-24
25	118	-13
37	137	67
58	129	95
90	107	82

Table 2. Residual stresses on the internal surface of the pipe.

Distance from Weld Centerline (mm)	Axial Residual Stresses (N/mm^2)	Hoop Residual Stresses (N/mm^2)
0	-81	191
24	-135	-139
57	-122	-117

3.2. Tensile strength

In order to determine the weld's mechanical properties, two tension tests are conducted (a flat strip normal to the girth weld and a round bar along the girth weld). This test is accomplished by Zwick tension test machine with 600 KN capacity and 10 mm/min tensile rating according to EN 895 standards. Based on the standard, the ratio of tensile strength on yield stress is less than 0.9. Table 3 demonstrates the tension test results. No fracture from the weld gap has happened.

Table 3. The results of the tensile test.

Specimen	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation%	Y/T
Flat Strip (normal to girth weld)	633	712	20	0.89
All Weld (round bar along the girth weld)	505	599	13	0.84

3.3. Charpy impact strength

In order to determine the impact strength of steel, Charpy test with 10 mm full thickness is performed in the weld zone, heat-affected zone and base steel. This test is done by Roell/Amsdler pk 450 machine with a capacity of 450 Joules at the temperature of -10 °C, according to EN 875 standard. Table 4 shows the Charpy test results. These results show that Charpy energy has increased from the weld zone toward the heat-affected zone.

Table 4. The results of Charpy impact test.

Specimen	Charpy energy (J) Test 1	Charpy energy (J) Test 2	Charpy energy (J) Test 3	Mean Charpy energy (J)
WELD (weldment cross section)	33	48	54	45
WELD (V notch in axial direction)	63	51	36	50
HAZ (weldment cross section)	123	150	114	129
BASE (V notch in Hoop direction parallel to girth weld)	400	376	408	395

3.4. Hardness

Hardness test in the section perpendicular to the hoop girth weld is done by Brinell method. Figure 3 displays the location of test points. To compare the measured values with the standard and to gain the yield strength and ultimate tensile strength, the Brinell hardness unit is converted to Vickers. According to ASTM E10 standard, this experiment shows the weld hardness in an allowable range below 348 Vickers. Also, the difference between weld hardness and the base metal hardness is less than 100 Vickers. Tables 5 and 6, respectively, illustrate the hardness in the weld zone and HAZ based on Brinell hardness criteria. As can be seen, in various zones of the weld gap, the filling pass has the highest degree of hardness. The heat affected zone beside the weld metal has the lowest hardness. The yield strength and ultimate tensile strength of the different weld zones are estimated from the hardness values using the following equations [21]:

$$YS = 2HV + 105 \tag{1}$$

$$UTS = 3.45BHN \tag{2}$$

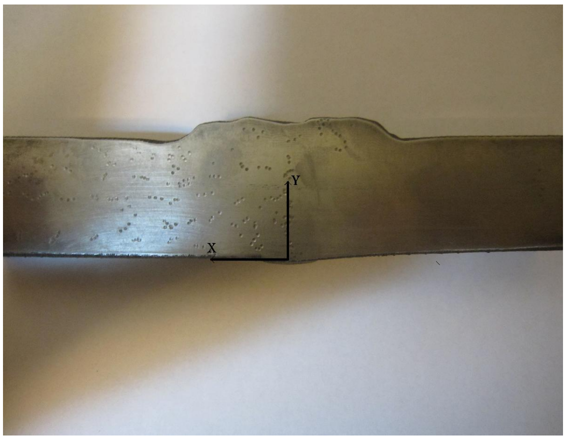

Fig. 3. Examined cross section on the hardness test.

Table 5. Hardness in different weld zones.

AVE.	1	2	3	Distance From Root Pass	Weld Pass
150	151	150	149	1	Root
149	150	149	149	2.5	
150	155	152	144	5	Hot
162	174	154	157	6.5	
176	188	172	168	8	Filling
178	178	175	181	9.5	
181	179	177	187	10.5	
151	151	149	153	12	
153	154	150	154	15	
149	147	148	152	18	Cap
121	115	124	125	22	

Table 6. Hardness in heat affected zone.

AVE.	1	2	3	Distance From Root Pass		HAZ
				X	Y	
147	151	138	151	7	1	Root
117	116	127	108	15	1	
131	132	134	126	15	2	
139	135	135	146	7	2.5	
135	137	134	134	20	3	
135	137	137	131	26	3	
150	152	154	145	17	6	Hot
146	150	145	142	20	6	
145	142	145	148	27	6	
158	158	161	154	27	8	Filling
149	147	150	151	15	10	
148	147	149	148	19	10	
152	154	152	150	22	10	
159	162	159	156	28	10	
158	160	158	155	18	12	
150	149	155	146	18	12.5	
158	160	160	154	25	13	
156	153	159	156	31	14	
153	154	149	157	20	15	
156	154	149	164	18	17	Cap
153	158	154	148	21	17	
153	145	154	159	28	18	
148	142	144	157	35	18	
149	148	147	153	17	19	

4. Discussion

In order for estimating the structural static strength and impact strength in different parts, some new parameters are defined. Figure 4 illustrates the diagrams of the yield strength versus the dimensionless parameter R_{ya}[1] (sum of the surface residual stresses over the yield strength) on the internal and external surfaces of the pipe away from the weld gap. This dimensionless

[1] Residual stress, Yield strength, Average

parameter represents the average surface residual stresses on the local yield strength obtained from the hardness test.

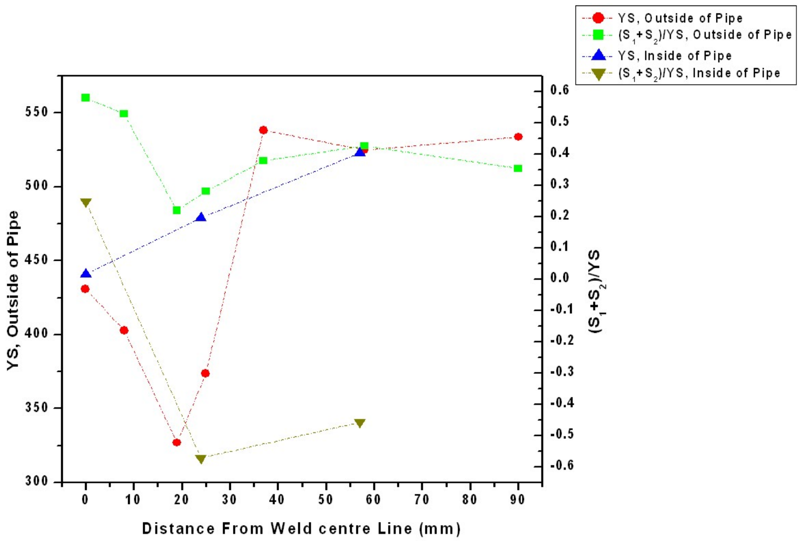

Fig. 4. Yield strength versus the R_{ya} on the internal and external surfaces of the pipe.

For better presenting the influences of residual stresses on the yield strength of the weld, Figure 5 is drawn to show the dimensionless parameter R_{ym}[2] (maximum tensile residual stresses over the yield strength) and R_{ya} in the internal and external surfaces of the pipe. As can be seen, the R_{ym} towards R_{ya} is steeper in the weld zone. The obtained results are in accordance with the reported results in Ref [2].

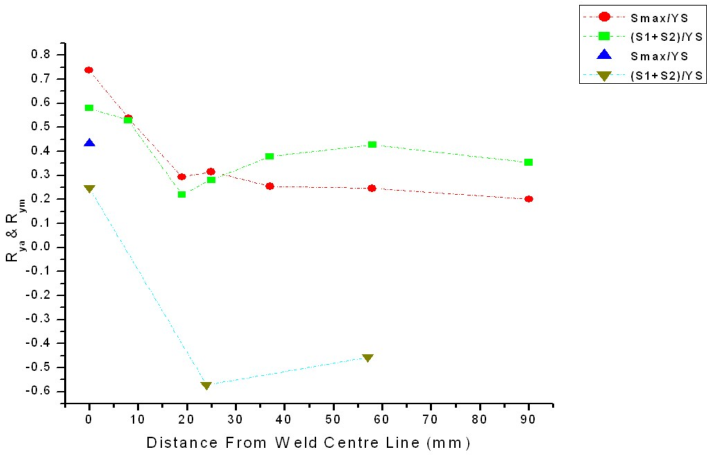

Fig. 5. R_{ya} and R_{ym} on the internal and external surfaces of the pipe.

Figure 6 presents the ultimate tensile strength changes versus the dimensionless parameter R_{u2}[3] on the internal and external surfaces of the pipe. This dimensionless parameter is the subtraction of two-dimensional residual stresses over the local ultimate tensile strength obtained from the hardness test.

In order to depict the effect of residual stresses on the impact strength, Figure 7 displays dimensionless parameter R_{u3}[4] (subtraction of three-dimensional stresses over the ultimate tensile strength) and R_{u2} in the internal and external surfaces of the pipe. As seen, in the weld and the zones around the weld, graphs of R_{u2} and R_{u3} are overlapped while away from the weld gap, R_{u2} shows further reduction. The obtained results are in accordance with the reported results in Ref [21]. Due to the high quality of the welds, all the samples were fractured from the heat-affected zone.

Although residual stresses do not directly affect the tensile properties, tensile test results can be used for evaluation of these stresses. The ratio of residual stress to the actual yield strength can be used in order to study the reduction of structural static strength due to the presence of residual stresses. As the level of tensile residual stresses in the weld center is very high, a decrease in structural strength would seem more important (the residual stress reaches to 60 percent of weld yield strength). To evaluate the effect of residual stresses on the weld tensile strength, the R_{ya} criteria obtained from dividing the average residual stress over the yield strength (in the point of hole drilling and hardness tests) was designed; and its curve is plotted in Figure 4. In order to be able to compare the R_{ya} with R_{ym}, the ½ coefficient for averaging is ignored. Clearly, in these curves, the

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2 Residual stress, Yield strength, Maximum
3 Residual stress, Ultimate tensile strength, Two-dimensional
4 Residual stress, Ultimate tensile strength, Three-dimensional

designed ranges of this dimensionless parameter are located between ±0.6. The maximum and minimum of these criteria happen in the weld center (external surface) and the HAZ (internal surface) of the pipe, respectively. Also, the difference in the maximum and minimum of R_{ya} criteria on the external surface of the pipe is about 0.4 while this difference in the internal surface of the pipe reaches 0.8. Due to this critical state, the reduction of static strength in terms of quantity is happening on the external surface of the pipe (in the center of the weld gap). (The results of table 1 show the yield strength of the weld zone is lower than the HAZ). In the internal surface of the pipe, R_{ya} has a remarkable change (the average stresses are converted from tensile mode to pressure mode) and it approximately has changed 2 times of external surface of the pipe. The maximum difference in the yield strength on the external surface of the pipe is between HAZ and base metal, while R_{ya} criterion detects the greatest difference in the weld metal and HAZ. Furthermore, R_{ya} diagram has more uniformity compared to the yield strength diagram. The obtained results are in good agreement with the reported results in Ref [3].

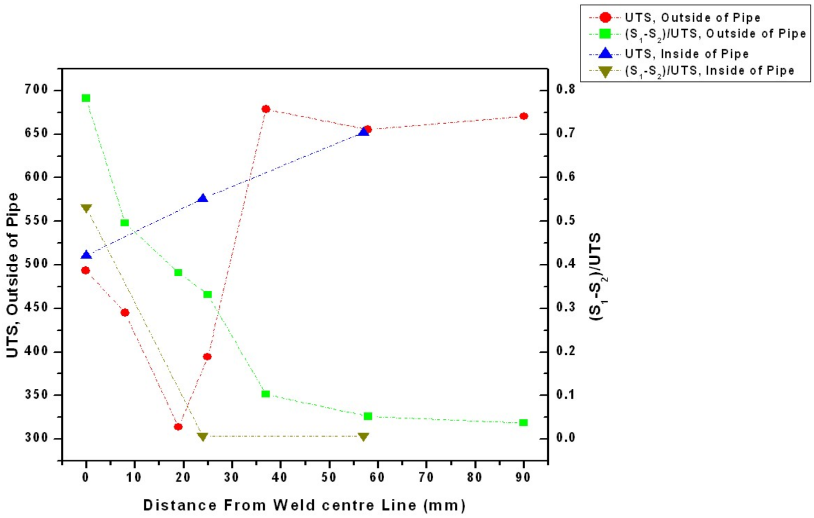

Fig. 6. The ultimate tensile strength changes versus the R_{u2} on the internal and external surfaces of the pipe.

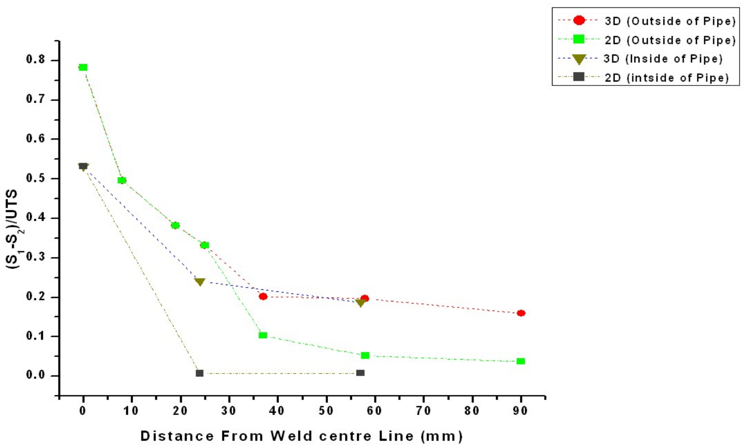

Fig. 7. R_{u3} and R_{u2} on the internal and external surfaces of the pipe.

For a better understanding, the effect of residual stresses on the reduction of structural yield strength, another criterion R_{ym} (obtained from dividing the maximum residual stress over the structural yield strength) is evaluated (Figure 5). Increasing the quantity of this criterion shows a reduction in the tensile mechanical properties such as yield strength as the residual stress magnitude is close to plastic flow stresses. The quantities of R_{ym} diagram in the weld zone and HAZ adjacent to the weld is more than R_{ya} and in greater distances away from the weld, it is less than R_{ya}. It seems, due to the hydrostatic nature of residual stresses, R_{ya} is a more appropriate criterion. So, the concomitant use of R_{ym} criterion (in the weld gaps and surrounding zones) and R_{ya} criterion (in zones away from the weld gap) are suggested as it will bring more safety on evaluating the reduction of structural static strength. On the tensile test, the rupture happens in the HAZ is consistent with maximum R_{ym} criteria zone, which confirmed that residual stresses in addition to hydrostatic nature also affect the static behavior of the structure. In the internal surface of the pipe (the only evaluated one point), the recent criterion is more than the primary criteria. In a Charpy test, the base steel shows the greatest strength. Moreover, the weakest impact strength in the weld zone is especially seen in the hoop direction. Increasing the impact strength from weld to base steel will follow a non-linear behavior. The impact strength of the weld zone toward the heat-affected zone increased by two-times while the impact strength increased from the heat-affected zone of the base steel for about 4 times. To evaluate the effect of residual stresses on the impact resistance of the structure, R_{u2} criterion obtained by dividing the residual stress difference on the ultimate tensile strength of structure (in the point of hole drilling and hardness tests) is introduced, and its curve is plotted in Figure 6. As it is clear in this figure, the ultimate tensile strength curve follows the same trend with the yield strength curve (Figure 4) and only its amount has increased slightly. So, for the ultimate tensile strength curve, we can consider the similar interpretation used for the yield strength curve. The range of this designed dimensionless parameter is between zero and 0.8. As it is indicated in this figure, this criterion in the weld gap of the external surface of the pipe has its highest value and its value away from the weld gap decreases with a very sharp slope. This slope is perfectly consistent with the rising trend of reduction in impact resistance and represents more effects of residual stress differences on the impact resistance of the weld metal, HAZ and base steel. The ultimate tensile strength represents the maximum tensile stress bearing of the structure and determines the material toughness with the elongation parameter. This reduction inside the pipe followed the same trend. R_{u3} according to the difference between the maximum and minimum of three-dimensional residual stresses on the ultimate tensile strength is designed and its curve is plotted to be compared with R_{u2} in Figure 7. As it is clear, in the weld gap and HAZ adjacent to the external surface of the pipe, two criteria are overlapped due to opposite directions of peripheral and axial stresses, but at longer distances, they take apart from each other and R_{u3} diagram is reduced with lower slope. Consequently, it seems that due to the effect of plane stresses in thin-walled pipes, R_{u2} criteria is more appropriate to describe the reduction trend of the impact resistance of the weld.

5. Conclusion

According to the obtained results in this study, it was concluded that:

- Low tensile strength in the weld in comparison with the residual stress led to more structural strength reduction percentage. In addition, the elongation has declined, which along with a decrease in the tensile strength, brings toughness and impact strength reduction.
- Weld impact strength reduction in circumferential direction is more than the axial direction which is due to the higher tensile residual stresses in the circumferential direction.
- The maximum and minimum R_{ya} criteria happened in the center of the weld gap on the external surface and HAZ on the internal surface of the pipe, respectively. Thus, the weakest point at static test is predicted to be in the center of weld on the external surface of the pipe which is consistent with tensile test results.
- The level of R_{ym} criteria in the weld and near it is more than the R_{ya} criteria, while in further distances from the weld gap, it is less than R_{ya}.
- R_{u2} criterion on the external surface of the pipe has the highest amount and reduces with a very sharp slope far away from the weld gap. This criterion is perfectly consistent with the reduction of the impact resistance.
- In the weld and its vicinity, R_{u3} and R_{u2} are consistent, but at further distances they take apart from each other and the slope of R_{u3} decreased in comparison with R_{u2}. R_{u2} is more appropriate criteria for describing the impact strength reduction due to welding.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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