Microhardness and Elasticity Study of Fatigue Tested Weld Samples

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Abstract. A chemical analysis of low-carbon steel St3sp was carried out and the arc welding process used, then probes proceeded to mechanical testing such as tensile test and low-cycle fatigue test. A total inclusion of weld defect in the specific welded sample and especially in the cyclic loading specimens has been discovered. A premature fracture was revealed below the plastic limit in some probes during the tension and low-cycle test. A micro structural examination and micro hardness measurements was done in order to determine the reason of fracture. To determine the heterogeneity in mechanical properties the elastic modulus distribution has been calculated due to relationship between the micro hardness and material strength.

Introduction

The heterogeneity problem for thermal processed and low-cycle damaged steel has very high actuality due to necessity of modeling of stress and strain state and lifetime estimation for structures [1,2]. This work fills the gap in the field of experimental basis and initial data for low-carbon steel structure modeling problem [3].

The heat of the arc causes both the core wire and the flux covering at the electrode tip to melt off as droplets. The molten metal collects in the weld pool and solidifies into the weld metal. The lighter molten flux, on the other hand, floats on the pool surface and solidifies into a slag layer at the top of the weld metal.

Materials and Equipment

A flat plate steel material was cut to size and the edge preparation was carried out by creating a groove of 30° on each end of the flat steel in order to get a 60° groove angle with root face of 3 mm. The input current was I= 110 A, and the voltage V=28 V. This sample was to be welded then cut into sizes according to the required test to be done. The standard filler material of mild steel ER70SG/2.4 was used for welding. After welding, these samples were supposed to be cut and polish.

Chemical composition of the steel was estimated by spectral analysis on Spectroport-F set-up.

Test samples for the cyclic tests are carried out to predict fatigue failure of specimens to serve as indication of structure failure when all hypotheses of specimen and real life structure is combine. The use of the servo hydraulic Instron 8802 machine will enable to detect zone and fatigue limit.

Mechanical Tests

The un-notched smooth tensile specimens were prepared to evaluate transverse tensile properties of the joints such as tensile strength and yield strength. Figure 6 represents tensile tests samples
produced in accordance to standard. The tensile test was conducted with a 40 ton electro-mechanical controlled universal testing machine Z600 Zwick Rowell.

In the Table 1 the corrected results of tensile test for 8 samples are shown. Except size, the table includes the proportionality limit $\sigma_{p0.2}$, breaking point $\sigma_m$ and elongation $\delta$. Two samples were broken at low stress value so were removed for any further analysis (No.6 and 10).

Table 1. Corrected tensile test result.

| No | $S_b$, [mm] | $L_0$, [mm] | $\sigma_{p0.2}$, [MPa] | $\sigma_m$, [MPa] | $\delta$, % |
|----|-------------|-------------|------------------------|------------------|----------|
| 1  | 84.08       | 52.00       | 328.35                 | 484.50           | 22.18    |
| 2  | 85.67       | 52.00       | 322.08                 | 477.24           | 20.95    |
| 3  | 73.92       | 52.00       | 314.62                 | 488.12           | 23.55    |
| 4  | 84.16       | 52.00       | 335.97                 | 482.68           | 21.72    |
| 5  | 80.67       | 52.00       | 335.90                 | 485.46           | 25.93    |
| 7  | 83.21       | 52.00       | 323.45                 | 484.79           | 21.83    |
| 8  | 85.91       | 52.00       | 318.22                 | 479.69           | 20.91    |
| 9  | 83.37       | 52.00       | 340.22                 | 485.18           | 23.20    |

Amongst the ten specimens used for the test, nine of the specimens were broken not at the welded portion but on the base metal. This can only interpret a good weld done with little or no defect.

The un-notched smooth cyclic loading specimens were prepared to evaluate fatigue properties under low cyclic loading. Two points were obtainable from the tensile test results like the average tensile loading and the average Rp 0.2. An interval between these two values serves as maximum starting point for the fatigue loading for each specimen. This cyclic loading was constant on the specimens under a constant frequency of 5 Hz until fracture and complete rupture occurs on the specimen.

The data obtain from low cyclic loading test shown in the Table 2. Separation line here means the zone between the base metal and welded zone. Undercut defects was revealed after the surface polishing and etching. Fatigue test was carried out with auto level loading cycle for all prepared specimens. The peak-to-peak value $\sigma_{max}$ here corresponds to the proportionality limit $\sigma_{p0.2}$.

Table 2. The data obtain from low cyclic loading test.

| No | Load, [MPa] | Section, [mm²] | Reference Input, [kN] | Rupture time of specimens, [sec] | Number of cycles | Rupture point of specimen | Visual inspection of defect |
|----|-------------|----------------|----------------------|----------------------------------|-----------------|--------------------------|----------------------------|
| 1  | 440         | 216            | 95.04                | 228                              | 1140            | Welded Zone              | Seen                       |
| 2  | 400         | 221.76         | 88.704               | 575                              | 2875            | Welded Zone              | Seen                       |
| 3  | 360         | 221.81         | 79.8516              | 4600.5                           | 23002.250       | Separation line          | Undercut                   |
| 4  | 380         | 213.64         | 81.18                | 2819                             | 14094.5         | Welded Zone              | Seen                       |
| 5  | 340         | 209.5          | 71.230               | 14062                           | 70311           | Welded Zone              | Seen                       |
| 6  | 420         | 211.8          | 88.950               | 4854.5                           | 24272           | Base Metal                | No                         |
| 7  | 370         | 210.3          | 77.810               | 15555.6                          | 77777.750       | Base Metal                | No                         |
| 8  | 390         | 211.5          | 82.471               | 2932                             | 14660           | Separation line          | Undercut                   |
| 9  | 410         | 207.75         | 85.176               | 2655                             | 13273           | Welded Zone              | Yes                       |

The results of the microhardness measuring for three samples are presented in Table 3 and on Figure 1. The higher values accord to weld zone, the lowest correspond to HAZ and base metal is on the right part of curves.

Table 3. Summary data for microhardness measurement.

| Pieces No. | Number of Cycles | Micro hardness $H_{50}$ for Welded zone, [MPa] | Micro hardness $H_{90}$ for Base metal, [MPa] |
|------------|------------------|-----------------------------------------------|-----------------------------------------------|
|            |                  | max               | min               | max               | min               |
| 1          | 1140             | 2629              | 2392              | 1845              | 1749              |
| 3          | 23002.250        | 2546              | 2004              | 1845              | 1661              |
| 7          | 77777.750        | 2392              | 2004              | 1845              | 1540              |
Discussion and Results

Figure 2 shows the microstructure of the following different zones of welded probe: the base metal (left), the weld (center) and the heat affected zone (HAZ) on the right.

Analysis of the microstructure of the base metal, weld metal and heat affected zone of the sample number 7 was performed using metallographic microscope "Neophot-32". Composition of pearlite and ferrite was seen with the print of the indenter of the micro hardness test. The formation of pearlite and ferrite in base metal is composed of 20/80 respectively. For weld zone and HAZ it changes due to thermal processes.

So the microstructure analysis shows that the base metal is a ferrite and pearlite having a grain size of 11-12 mkm on a scale corresponding to an average grain diameter ≈ 7 microns (see Figure 3, c). The structure of the weld metal is also made up of ferrite and pearlite (see Figure 3, a) with columnar crystals of cast metal. The HAZ is made up of Widmanstätten figures (see Figure 3, b). The width of the HAZ zone is about 1,5 mm. In different areas of heat affected zone is observed fine-grained ferrite-pearlite structure with a high degree of dispersion. Figure 3, b shows a micro crack with the 1,7 mm length in the HAZ of sample number 7. In the weld zone of this probe the micro crack with 1,2 mm length was revealed also.
To define the mechanical properties of material, such as elastic modulus, it is necessary to analyze not only the chemical content but the phase composition also. In case of weld and low-cycling of steel St3ps it has Inhomogeneity in mechanical properties and phase. So it is difficult to explain the mechanical properties from structure and therefore necessary to find another way. One of them is the micro hardness definition that is connected to strength of material.

In a commonly used method the elastic modulus can be obtain from a complete cycle of loading and unloading to obtain a data for analysis according to a model of the deformation of an elastic half space by an elastic punch which relates the contact area at peak load to the elastic modulus [4]. It is a complex approach and thus demands an indentation diagram technique.

Another way used to analyze the elastic modulus of coating and layers. Known dependence of theoretical strength of material:

\[ E = \sigma_{\text{theory}} \cdot 4\pi (1 - \nu^2), \]  

(1)

where \( \sigma_{\text{theory}} \) is the theoretical strength of crystal and \( \nu \) - Poisson ratio (for steel \( \nu = 0.3 \)). The real strength of material in tenfold less than theoretical, so (Eq.1) will be written as:

\[ E = 10 \cdot \sigma_b \cdot 4\pi (1 - \nu^2), \]  

(2)

where \( \sigma_b \) is the breaking point.

But in (2) used only one tensile stress for whole probe. Average breaking point for 8 tensile test samples will be: \( \Sigma \) (Rm/8) = 483.33 MPa. So the average elastic modulus for steel welded probes given by (2) is approximately \( E \approx 0.553 \times 10^5 \) MPa. It is lower than the standard value for cold steel.

Nevertheless to identify the local strength by micro hardness it is possible to use the dependence:

\[ \sigma_b = 3.5 \cdot HB, \]  

(3)

where HB – is the Brinell hardness.

To obtain the HB value from micro hardness HV it is necessary to consult the reference table or special curves. The results of calculation by (2) and (3) are shown in Table 4. Actually, for this range of hardness the HB equal HV/10 within engineering accuracy.

| Pieces No | Number of Cycles | Elastic modulus E for welded zone, \( \times 10^5 \) [MPa] | Elastic modulus E for base metal, \( \times 10^5 \) [MPa] |
|-----------|------------------|-------------------------------------------------------|-------------------------------------------------------|
|           |                  | max | min | max | min |
| 1         | 1140             | 1.05| 0.956| 0.736| 0.700|
| 3         | 23002,250        | 1.02| 0.816| 0.736| 0.664|
| 5         | 77777,750        | 0.957| 0.816| 0.736| 0.616|

So these values of elastic modulus characterized the heterogeneity of local mechanical properties and could be used as an approximation for further numerical modeling.
Conclusion

The main result of this work is establishing the heterogeneity caused by weld and low-cycled fatigue due to micro hardness measurement method for further use in numerical analysis. The mechanical properties and structure evaluation after the weld and low-cycle loading is significant also. The differences in failure for low-cycling fatigue test probes caused by weld defects and heterogeneity could be modeled both by mechanics of continua and fracture mechanics.

Common defects were noticed on some welded samples, and these samples during the tensile test were broken on the welded zone under the normal estimated tensile strength and before the elastic limit. This failure could be as a result of one of the following reasons: poor welding procedure specification, poor welding skills, amongst others. Micro structural examination and micro hardness measurements was done in order to determine what exactly could be the reason of this catastrophic failure. The focus of the research is to estimate the inhomogeneity of specimen due to weld, so as to prepare the initial data for numerical modeling. The structural research revealed the differences in mechanical properties conditioned by phase distribution and carbon content in weld, heat affected zone and base metal. In order to reach this point, a chemical analysis of the material was carried out and the welding process used, then probes were proceeded for mechanical testing such as tensile test, fatigue test, and micro hardness test. A total inclusion of weld defect in the specific welded sample and especially in the cyclic loading specimens has been discovered. Knowing the mechanical behavior of this material during loading and failure will help us to predict the time of maintenance of bridge structures so as to avoid catastrophic failure leading to heavy loss of lives and properties thereby beneficial to road users, investors and the nation as a whole.

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References

[1] Ivica Čamagić et al, Influence of mechanical properties microstructural heterogeneity of welded joint constituents on tensile properties and fracture toughness at plane strain $K_{IC}$, Structural integrity and life, 14 (2014) 45-49

[2] M. Toyoda, M. Mochizuki, Y. Mikami, Metallurgical and Mechanical Heterogeneity in Weld Materials Considering Multiple Heat Cycles and Phase Transformation, Materials Science Forum, 512 (2006) 19-24.

[3] Lepov V.V. et al, Stochastic simulation of fracture of a damaged heterogeneous medium, Physical Mesomechanics, 5(2002), 23-42.

[4] Oliver W.C., Pharr G.M. An improved technique for determination hardness and elasticity modulus using load and displacement sensing indentation experiments, Journal of Material Research, 7 (1992) 1564-1583.