Experimental and numerical evaluation of the fatigue behaviour in a welded joint

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Abstract: Welded joints are an important part in structures. For this reason, it is always necessary to know the behaviour of them under cyclic loads. In this paper a $S - N$ curve of a butt welded joint of the AISI 1015 steel and Cuban manufacturing E6013 electrode is showed. Fatigue tests were made in an universal testing machine MTS810. The stress ratio used in the test was 0.1. Flaws in the fatigue specimens were characterized by means of optical and scanning electron microscopy. SolidWorks 2013 software was used to modeling the specimens geometry, while to simulate the fatigue behaviour Simulation was used. The joint fatigue limit is 178 MPa, and a cut point at 2 039 093 cycles. Some points of the simulations are inside of the 95% confidence band.

Keywords: Welded joint, fatigue, $S - N$ curve, AISI 1015, E6013, numerical simulation

1. INTRODUCTION
Welded joints have an important role at the present time. Practically in all the structures are these types of joints. Manual metal arc is a process commonly used to make the joint. This is characterized by the application of heat focused in the area to join. In the welding bead, the temperature reaches high values that are able to fuse the metal. However, the temperature decreases from the welding bead to the base metal. This causes a variable heat treatment in the welded joint that influences in the final metallographic structure of each area according to the maximum of temperature that has reached, and also in its mechanical properties. In this sense, it is possible to define three different zones in the welded joint: contribution material (CM), heat affected zone (HAZ) and base material (BM). HAZ has a special interest. In this, the BM doesn't melt, but that is due to the high temperatures reached during the welding, in it occurs important metallographic transformations and also in its mechanical properties. Some investigations¹ define the HAZ as metallurgical notch, due to the reduction of the tenacity that happens there.

Fatigue is one of the phenomena that influence the most in the useful life of the elements of machines and structures requested by cyclis loads. Fatigue cracks begin in a local flaw of the structure. Fatigue cracks begin in a local flaw of the structure. In fact, the own geometry of the bead already constitutes a geometric discontinuity that turns out to be
a stresses concentrator. The “local approach”, which is based on the location of the denominated hot spots, has great application in the study of the welded joints. According to this approach, if in any point of the joint the stress value are equal or higher that the yield limit, a fatigue crack begins. The S-N curves is based on the medium fatigue life or in a given failure probability. The generation of the S-N curve of a material requires many tests. Due to the high statistical dispersion, the results are grouped in a confidence bands. A part of this dispersion can be attributed to test errors, but it is a property of the physical phenomenon that which provokes to carry out a great number of tests in order to determine the confidence band with enough precision. Therefore, to characterize a material to fatigue supposes a very high cost, due to the quantity of necessary test specimen, the complexity of the test machines and the necessary time to carry out each experiment.

Design modern techniques are supported in the CADCAM technologies. Thanks to the quick development of the computers, today is possible to carry out calculations and to simulate complex experiments that reproduce the real phenomenon with certain approach grade. SolidWork software uses the theory of the accumulated damage (also called Miner’s lineal damage rule) for the studies to fatigue[2]. In this it is supposed that a load cycle causes a permanent damage that can be measured[2].

Lineal damage rule doesn’t consider the effects of the load sequence. This way, it predicts that the damage caused by the stress cycle is independent from where it takes place in the load history. It also supposes that the rate of accumulation of damage is independent of the stress level. This can take to differences with the experimental values, because like it is known the cracks of fatigue begin and develop with different behavior at different stress levels. Another difficulty that it can be observed to this rule is that it doesn’t consider the different stages of the development of the cracks of fatigue. In a general way, this is a factor that affects all the fatigue classic approach. In this sense, Fracture mechanics can offers better results.

In this study, it is pursued as objective to show the S-N for a butt welded joint in which is used AISI 1015 steel as BM and the CM is the E6013 electrode of Cuban manufacturing, besides a methodology to simulate by means of Finite Element Method (FEM) the answer of the joint under the action of the variable loads.

2. MATERIALS AND METHODS
To carry out this study AISI 1015 steel was used as BM. This is steel that has a good soldability. The BM for the welding was in a plate of dimensions 500 mm x 600 mm x 4 mm. The joint was carried out without edges preparation, with beads to both sides assisting to the dimensions proposed in the Figure 1.

![Figure 1. Welded specimen geometry. a) The joint is carried out without edges preparation. b) Dimensions of the welded specimen. c) Specimen welded for fatigue test.](image)

Chemical analysis of a square sample of side 5 cm and thickness 4 mm to check that the material used in the experiments was AISI 1015 steel was carried out in an ARL 3460 cuantometer. The results of this analysis is shown in the Table 1. On the other hand, the mechanical properties of the material according to the bibliography are in the Table 2.[3]
Table 1. Chemical composition of the AISI 1015 steel[3].

| AISI 1015 steel | Elements          | Composition: |
|-----------------|-------------------|--------------|
|                 | Carbon (%)        | 0,13 - 0,18  |
|                 | Manganes (%)      | 0,30 – 0,60  |
|                 | Silicon (%)       | 0,17 – 0,37  |
|                 | Sulphur (%)       | ≤0,05        |
|                 | Phosphurus (%)    | ≤0,04        |

| Typical Measure | 0,166 090         |
|                | 0,504 210         |
|                | 0,027 460         |
|                | 0,005 780         |
|                | 0,013 850         |

Table 2. Physical and mechanical properties of the AISI 1015 steel[3].

| Properties | $\sigma_B$ (MPa) | $\sigma_f$ (MPa) | $\mu$ | $\rho$ (kg/m$^3$) | $\alpha$ (1/ºC) | $\delta$ (%) | $\psi$ (%) |
|------------|------------------|------------------|-------|-------------------|-----------------|--------------|------------|
|            | 420              | 315              | 230   | 0,29              | 7 870           | 119 x 10$^{-7}$| 39         | 61         |

Welded joint was carried out by means of Manual Metal Arc. E6013 Cuban manufacturing electrode was used. Table 3 shows the mechanical properties of the deposit.

Table 3. Mechanical properties of the CM[Manufacturer data].

| Properties | $\sigma_B$ (MPa) | $\sigma_f$ (MPa) | $\delta$ (%) | $\psi$ (%) |
|------------|------------------|------------------|--------------|------------|
|            | 431 – 510        | 392              | 20 - 28      | 35 – 60    |

The values of the welding process parameters to carry out the joint are in Table 4.

Table 4. Welding process parameters.

| Current (A) | Voltage (V) | Number of beads | Welding velocity (mm/min) | Number of electrodes (*) | Total time(*) (s) |
|-------------|-------------|-----------------|---------------------------|--------------------------|------------------|
| 90 – 120    | 24 – 26     | 2               | 59,57 – 79,42             | 0,421                     | 81,22 – 60,91    |

TRI-ARC 504. Rectifier with capacity between 70 A -500 A y 23 V – 40 V.

(*) For one specimen

The welded joint studied was tested to fatigue. For it was necessary to determine the values of the parameters of the load cycle. The regime of load was asymmetric tensile. The first parameter was the maximum stress (1). The maximum stress of the cycle in a first load level it is considered a fraction 2/3 of the AISI 1015 steel yield limit.

$$S_{max} = \frac{2}{3} S_y$$ ..................................................(1)

The value of the maximum stress calculated by means of the previous expression is equal to $S_{max} = 210$ MPa to which corresponds a maximum load $P_{max} = 33,60$ kN.

Tests will be carried out at different load levels. The following load levels will be calculated according to the results of previous level. This is due to the great dispersion that exists in the fatigue test results. The logie that is used to determine the following load levels is the following one: the load value is diminished until the specimen tested reach equal or overcome the value of 1 500 000 cycles, for those correspond the fatigue limit in case of the joints according to ASTM E 739 - 91[4] standard. The asymmetry ratio of the cycle $R = 0,1$. The frequency of application of the load is 14 Hz. As failure criterion is used “total fracture”. Test is interrupted when 1 500 000 load cycles are applied. The temperature of the laboratory was of 20 ºC ± 2 ºC. Fatigue test were carried out in a universal machine test MTS810.
The geometric performance was made in SolidWorks 2013 software and for the simulations the package Simulation. To make the simulations the methodology that appears in the Figure 2 is proposed.

Figure 2. Proposed methodology to the joint fatigue simulation.  
Figure 3. Load history curve.

The geometric model is the same that appears in the Figure 1. The second point of the methodology proposes the flaws creation. This is because simulations were carried out in the specimens without flaws, the software showed that the specimen failure occured in the section change, however, in the BM, what doesn't happen this way in the real welded joints. Next one runs a static study, considering that the applied load is the maximum of the load cycle. The time curve (Figure 3) models the variation of the load in the time. After the load curve a fatigue study is carried out which shows that it is possible to obtain the number of cycles that should fail the specimen.

3. RESULTS

According to what was expressed in the previous section experiments at 4 load levels were carried out. In the first load level a great dispersion of the number of cycles that the specimens failed was obtained. In the second level each specimen reach 1 500 000 cycles or higher that it is the value to stop the experiment. Then the third and fourth levels were used to adjust the intermediate values of the curve. Maximum stress for each load level are in Table 5.

| Level | Maximum stress $S_{\text{max}}$ (MPa) |
|-------|---------------------------------------|
| 1     | 210,00                                |
| 2     | 178,1                                 |
| 3     | 196,9                                 |
| 4     | 190,6                                 |

4. DISCUSSION

4.1. Fatigue test statistical analysis

For the study of the results of the fatigue test the ASTM E 739 - 91 standard is applied in this work. In a general way, it is possible to relate the fatigue life with the stress by means of the following equation:

$$\log N = A + B(S)$$

Where $A$ and $B$ are the coefficients to fit the equation and are equal to $\hat{A} = 11,775 716 240$ and $\hat{B} = -0,031 058 404$ respectively. However, equation (2) now is:

$$\log N = 11,77571624 - 0,031058404 \times S_{\text{max}}$$
To obtain equation (3) is necessary to assume a lineal model. If the lineal model is right or not is proved by means of the statistical test, based on the distribution $F$ that appears in the Table 2, page 5 of [4]. For a significance level of the 95% $F_{p} = 3.6823$, the calculated parameter has a value of 3.4577 being smaller than $F_{p}$. Therefore the hypothesis of lineality of the model is accepted.

4.2. Fractographic analysis

In this work was carried out a fractographic analysis to all the specimens tested to fatigue, by means of optic microscopy (MO) and scanning electron microscopy (SEM) using an Estereomicroscopic Zeiss Stemi SV11 and an electronic microscope JEOL JSM-6460LV, respectively. In a general way the cracks always begin in the flaw and develop themselves with a semielliptic front. The area of fragile break that happens because of the static overload of the specimen shows an extriction, characteristic of the break by tensile loads.

The observations of the specimen 20 are shown. It fails in the HAZ. The crack originates in the detail pointed out in the Figure 4 a) that it was identified by means of the penetrant liquids. From this point it began to develop that was growing by means of the well-known semielliptic front until reaching the critical crack size. An observation by means of SEM of the area where is this flaw are showed in the Figure 4 c). In its, the flaws is appreciated that has an initial lengthened shape with a longitude of 0.6923 mm and an approximate width 0.0385 mm.

![Figure 4. Specimen 20 fractographic analysis. a) Flaw identified by penetrant liquids. In this point the crack begin. b) Observation by means of MO. c) Observation by means of SEM.](image)

These defects and others that are not shown in this work are those that were modeled in the second step of the proposed methodology to carry out the welded joint fatigue behavior simulations.

4.3. Numeric simulation of the welded joint fatigue behavior

To carry out the study a solid mesh was used. Material model was lineal elastic and a type of finite elements was quadratic of high order. To check the model convergence several studies are carried out varying the size of the element until the results do not vary more than 5% of the previous analysis. In the Figure 5, the specimen with static load, constraints and mesh is shown.

![Figure 5. Specimen with load, constraints and mesh. Elements size: 1.233 mm.](image)

As it was already said before, the different specimens were modeled with flaws that constituted the places where the fatigue crack began; and therefore, where it should the fatigue failure happen. Flaws size was taken from characterization by means of SEM.
Twenty four specimens were modeled. The fatigue study is based on running a static study to a certain value of load (in the case of this investigation is carried out to the value of maximum load) and later on a load curve is generated as that of the Figure 3 and execute a fatigue study. Results are the accumulated damage and total fatigue life in the specimen. The last one is expressed in load blocks. The load blocks means how many times it is necessary to repeat the applied load event to the fatigue failure occurs. As in the studied specimen a load curve was generated to one second, the number of load blocks for the times that one cycle are in each second, how many cycles resists the specimen until the fatigue failure is obtained. The frequency of application of the load is of 14 Hz, and then each cycle repeats 14 times in each second.

As example of the obtained results, the simulated specimen 9 is shown in Figure 6. In this specimen, a flaw it is like that is shown in the Figure 4.

![Figure 6. Flaw location and size in simulated specimen 9.](image)

In the Figure 7 a) the results of the static study are shown. The biggest stress value is equal to 1 181 MPa. It is located in the stress concentrator, with a bigger value that the yield limit. This is in agreement with the local approach, in that point a fatigue crack begins.

![Figure 7. Specimen 9 simulation results. a) Maximum stress. b) Damage 9. c) Total life.](image)

In the Figures 7 b) and c) are the values of damage and the total life for the simulated specimen 9. As it is appreciated, in the concentrator is where the fatigue failure occurs.

4.4. Welded joint $S - N$ curve
The $S - N$ curve of the welded joint is shown in the Figure 8. The experimental curve was obtained from the experimental data, processed according to $^{[8]}$ like it has been described in the epigraph 4.2. The cut point is for a stress value of 178 MPa and 2 039 093 cycles. The simulations results are in this figure too. As we can see, some of them are between the 95% confidence bands.
5. CONCLUSIONS

1. A $S$ - $N$ curve was obtained. The equation that relates stress and number of cycles is

$$ \log N = 11.775716240 - 0.031058404 \times S_{\text{max}} $$

The fatigue cracks fatigue always began in a flaw, and then it grew following a semieliptic front crack until the break. Due to the great dispersion of the experimental results in each load level, is necessary to increase the quantity of tested specimen, with a better fit of the curve.

2. The proposed methodology can be used to simulate the welded joint fatigue behaviour by means of FEM. As we can see in Figure 8 some simulated points are inside the 95 % confidence bands, even on the fit equation. With several it doesn't happen this. First, it is possible to attribute this to the characteristic of the fatigue, where great dispersion always exists in the experimental results and second, to the classic fatigue theory, that do not consider the different fatigue stages. It is considered that to obtain better results it is necessary use the Fracture Mechanics in next research.

3. With the use of the numeric simulation software it is achieved a saving of time and resources, diminishing the costs of the experimentation considerably.

6. REFERENCES

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