Local Elasto-plasticity Behavior of HT780 Butt Welded Joint Analyzed by Digital Image Correlation Technique

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The present paper reports the results of experimental tensile tests, geometrical measurements and Vickers hardness tests in order to characterize the deformation process and the material failure of a HT780 butt welded joint specimens. In addition, the distribution of the strain fields on the surface of the samples is obtained by means of the digital image correlation technique. Furthermore, the relationship between the local stress-strain behavior and hardness is discussed from the results.

Key Words: Weld joint, Plasticity, Fracture, Digital Image Correlation, Hardness, Proof stress

1. Introduction

The use of high strength steel in steel structures is expected to reduce the weight, and then to save the transportation and construction costs, etc [1]. However, some aspects, for instance, the reduction of the joint strength caused by the welding heat and the concerns about the crack sensitivity due to the welding process, have to be still deeply investigated. Recently, new experimental laser welding methods have been developed and they are capable to reduce the heat input into the base metal, and therefore they aim to limit the reduction of the material strength. On the other hand, due to the inhomogeneous distribution of strength in the heated affected zone (i.e. HAZ), the geometrical deformation (e.g. angular distortion) and function of the welding conditions, it is difficult to measure and understand the process of deformation and the consequent crack formation in the high strength steels.

Strain gauges are used widely to measure the geometrical deformation and strain on specimen because the low cost and the relatively easy application. However, they can only measure the strains on narrow area with limited ranges, so they are not suitable to measure the precise distribution of strains and therefore they cannot give accurate information in complex cases where, for example, in the neighborhood of a welded area with an inhomogeneous distribution of material properties, leading to a complex strain distribution.

These days, the digital image correlation (i.e. DIC) [2], a non-contact measurement technique has been developed, and it gives a great help in the identification of the displacement/strain fields. In fact, the amount of deformation on the surface of specimen is calculated by comparing the pictures before and after straining process. Previous works using the DIC show the potential of this technique displaying the deformation during a welding process, large deformation due to mechanical load, local stress-strain behavior in welded joint and also stress distribution can be obtained by the strain one [c.f. 3]. However, the investigations in literature mainly deal with welded joint without reinforcement that is without considering the effect of stress concentration, and limiting the attention on the hardening behaviour in the HAZ, excluding to take into account a possible HAZ softening in the deformation process.

Therefore, the work presented in this paper aims to clarify the deformation and subsequent failure process on high strength steel welded joint having inhomogeneous and various distribution of...
strength by means of the DIC during tensile tests. Moreover, geometry measurements and Vickers hardness tests are carried out in order to discuss the role of these factors on the joint strength.

2. Experimental procedure and result

In this paper, we compared three different specimens. The first type is the base material of HT780 steel (referred in the text as base specimen), whereas the second two are obtained from a butt welded joint and composed by a HT780 base metal and a MG80 weld metal, where the welding was realized by arc technique (two passes on top and one single pass on the bottom surface, see Fig. 1). The two welded samples differ in the geometry of the welded area, with or without the reinforcement. Fig. 1 shows the geometry and the size of the joint samples.

In Fig. 2, the measurement of the angular distortions for the joints with and without reinforcement is reported. As it can be seen, the specimen with reinforcement presents a misalignment, in terms of distance from the center, and a difference in the amount of the reinforcement between the top and the bottom. In addition, it is shown that the specimen without reinforcement is about 1mm thinner than the one with reinforcement due to the surface cutting. The amount of angular distortion is about 1 degree, height of reinforcement from weld toe is about 3mm on the top, 1.5mm on the bottom and amount of linear misalignment is about 0.2mm for joint specimen with reinforcement.

In the subsequent Fig. 3, the contour field for the Vickers hardness test is reported, highlighting the formation of a softened material in the transition zone between the HT780 and the MG80 during the first and second welding pass, and a hardened one, at the bottom, induced by the third pass. The hardness average, in base metal, is about 271HV, the minimum hardness is about 174HV and maximum one is about 362HV.

Now, the monotonic tensile tests are carried out, at a constant displacement rate (1mm/min) for the base and the joint specimens. Fig. 4 shows the stress-strain curves (Gauge length/38mm) obtained in the experiments. Analyzing the results, it can be concluded that both the tensile strength and elongation of joint specimens are lower than in the base sample. However, the comparison of the tensile strengths for the two welded samples revealed an almost identical behavior. The only differentiating aspect regards the total elongation, which is higher for the sample without reinforcement. The joint efficiency, here identified by the ratio between strength of weld / Strength of base material, is about 0.92. The mechanical properties of base and joint specimens are listed in Table 1.

Table 1 Mechanical property of base and joint specimens

|               | Yield stress | Tensile strength | Elongation |
|---------------|--------------|------------------|------------|
| Base          | 762          | 817              | 21.5       |
| Joint with reinforcement | 630          | 755              | 9.93       |
| w/o reinforcement | 632          | 767              | 11.8       |

Yield stress(0.2% proof), Tensile strength unit : MPa Elongation : 38mm gauge

and the photography on the specimen for each nominal strain by the DIC. The images show that, in the base specimen, the necking occurs after a uniform straining process. For joint specimen without reinforcement, the maximum principal strain is concentrated in softened zone where the crack is formed. In the sample with reinforcement, the maximum principal strain initially tended to localize in stress concentrated zone but subsequently it shifted in the softened zone inducing the fracture there.

3. Relationship between local stress-strain behavior and Vickers hardness

Generally, it has been shown that material hardness is related to the strength. In order to observe the relationship between the local stress-strain behavior in the tensile test and Vickers
hardness, we created a series of stress strain curves using the local strain from DIC together with the nominal stress from the tensile test. The surface of all specimens is marked like mottled effect for measuring strains on specimen during experiments. In DIC method, displacement or strain is calculated by tracking the pattern on the surface. In order to enhance the quality of analysis, the surface is illuminated with light equipment. The results are reported in Fig. 6 together with proof yield stress at 0.2%, 1% and 2%. As can be seen from Fig. 6, strain gauges are defined by DIC method to gain local strain behavior, and then local stress strain curves are plotted using the local strains. The red dots in Fig. 6 shows proof stresses in each local stress strain curve. The curves refer to the welded specimen without the excess material, since the geometrical imperfection would induce an additional complication in terms of stress concertation. As shown in Fig. 2, the joint specimen is distorted, so the sample is rectified by chucking, and then the stress and strain curve is generated by applying a tensile load. As a further improvement, an initial stress occurring by rectifying distorted specimen has been applied to the proof yield stress from the local stress-strain curves. This factor can be obtained by means of FE analyses which simulate rectifying the specimen. In this way we obtained a distribution of
the initial stress that can be used as modifying proof stress (modified proof stress defines that original proof stress in Fig. 6 plus initial stress obtained by FE analysis). Finally, arranging the local proof stress and hardness results from the Vickers test, it is possible to plot the points in Fig. 7. In the graph the relationships between the 0.2 stresses and hardness in the softened HAZ (1,2), weld metal (Wp 1,2) and hardened zone (Wp 3), are reported, and as it is possible to see, the proof stress is increasing with increase of the hardness. The reason why the results on BM and HAZ3 aren’t plotted in this graph is that BM doesn’t receive the effect of welding heat and HAZ3 area is so narrow that it is difficult to link stress to hardness precisely. It is concluded that a possible explanation for the shorter elongation of the joint specimen with reinforcement can be a change in ductility in hardened zone, in addition to an increase of stress concentration. The red line in Fig. 7 shows the typical relationship between yield stress and hardness ($\sigma_f=HV \times 2.7$). In order to compare the amount of total gap from the red line to the plotted points before and after adding the initial stress to original proof stress, $R^2$ of a coefficient of determination, is calculated by equation (1)

$$\begin{align*}
R^2 &= 1 - \frac{\sum(y_i - f(x_i))^2}{\sum(y_i - \bar{y})^2} \\
&= 1 - \frac{\sum(y_i - f(x_i))^2}{\sum(y_i - \bar{y})^2}
\tag{1}
\end{align*}$$

where $y_i$ is proof stresses of plotted points, $x_i$ is Vickers hardness of plotted points, $f(x_i)$ is calculated proof stresses ($2.7x_i$), $\bar{y}$ is mean stress ($\Sigma y_i/n$). If $R^2$ value is large, the total gap from the red line is small and these points have good relation to typical relationship ($\sigma_f=HV \times 2.7$). In relationship between 0.2% proof stress and Vickers hardness of Fig. 7, $R^2$ before adding the initial stress in Fig. 7(a) is 0.3095 and after adding in Fig. 7(b) is 0.3428, so the result considering the initial stress becomes better than the one not considering. However, some points in HAZ1, 2 areas are a little far from the linear fitting line, so it is needed to consider better way of modifying yield stress in the future.

4. Conclusion

The work presented in this paper aimed to clarify the deformation and subsequent failure process by means of the DIC during tensile tests in addition to geometry measurement and Vickers hardness test. The result of them revealed that strain is localized in softening zone (HAZ1, 2) and stress concentration area, and finally localized strain leads to failure. And also observed proof stress has relation to Vickers hardness. However, it should be noted that the relationship between stress (strain) and hardness is obtained only based on the surface, and inner condition of specimens is not considered in this study.

Fig. 6 Local stress-strain curves and definition of proof stress

Fig. 7(a) Relation between stress and hardness / bef. revising

Fig. 7(b) Relation between stress and hardness / aft. revising

As a future work, elasto-plastic FE analyses will be carried out to better estimate the stress localization factor and therefore to improve the evaluation method for high strength steel weld joints.

Reference

1) K. Anami, T. Miki, H. Yamamoto, Y. Higuchi: Fatigue Strength of Welded Joint Made of high Strength Steel and Fatigue Strength Improvement, Journal of JSCE, 675, 1-55, pp.251-260,2001.
2) M.A. Sutton, J.J. Orteu, H. Screier: Image Correlation for Shape, Motion and Deformation Measurements, Basic Concept, Theory and Applications, Springer, 2009.
3) A. Demizu, H. Matsuda, S. Hetsugi, M. Morisaki, M. Uchino, Y. Ito, C. Morita: Fundamental Study on Improvement in Strain Measurement Accuracy of Digital Image Correlation Method, Journal of JSCE, 68(2), pp. 1 683-6 690, 2012.