EFFECT OF FATIGUE DAMAGE ON THE DYNAMIC TENSILE BEHAVIOR OF CARBON STEEL WELDED JOINTS

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ABSTRACT

In different engineering applications such as automobile and train crashes, the high speed impact of debris as well as the high speed manufacturing processes, makes it necessary to have a deep understanding of the dynamic behavior of materials and components. There are different experimental techniques to determine the constitutive material behavior. Several constitutive models have been proposed to predict the dynamic response of engineering structures. However, in all cases, initial damage-free material is assumed and the structures are without fatigue damage when tested. The dynamic response of fatigue damaged AISI 1018 steel welded joints subjected to impact loading is investigated in this work. The tensile Hopkinson bar apparatus is used in the dynamic experiments. Welded joints without post weld heat treatment are used. Samples subjected to previous high cycle fatigue are considered. An investigation of the failure modes is performed as well. Results show that previous fatigue damage affects the quasi-static and dynamic tensile behavior. The effect of the previous fatigue damage on the quasi-static and dynamic tensile behavior on the base material and the welded joint is compared. Previous fatigue damage has a detrimental effect on ductility of 1018 steel welded joints, principally under dynamic loading.

KEY WORDS: Impact loading, Welded joint, Hopkinson bar, Fatigue damage.

1. INTRODUCTION

Welding fabrication is one of the most common joining procedures of metallic structures. The vast majority of component fatigue failures take place at the welded connections [1]. Many of the welded structures and components are subjected to fatigue and impact loading.

It is well known that the mechanical behavior, such as yield stress, ductility and strength of materials, will change under different strain-rate loadings and temperatures [2]. An understanding of the deformation of metals over a wide range of temperatures and strain rates is important in metal forming, high speed machining, high velocity impact, penetration mechanics, explosive-metal interaction, and other similar dynamic conditions. Impact problems have been studied for long time. A complete material description for numerical simulation involves not only the stress-strain response, but also the damage accumulation and failure mode [3].

The dynamic behavior of different materials under the action of impact tensile loading has been investigated and reported in the open literature. The dynamic mechanical behavior of welded joints has been studied for low alloy steels [4] and for stainless steels [5-7]. The dynamic response of welded HSLA 100 steel was investigated in [4]. High velocity impact tests were performed on 304L stainless steel joints [5] using a compressive split Hopkinson bar. Different welding procedures were applied; Gas Tungsten Arc Welding (GTAW) [5], Shielded Metal Arc Welding (SMAW) [6] and Plasma Arc Welding [7]. The results show that the impact properties and fracture characteristics of the tested weldments depend strongly on the applied strain rate.

Little work has been done to evaluate the effect of previous fatigue damage on the dynamic response of materials and structures. The effect of fatigue damage induced by cyclic plasticity on the dynamic tensile behavior of materials has been reported in [8, 9]. No works are available related to the consequences of the previous fatigue damage on the dynamic behavior of welded joints. The AISI 1018 steel is a general purpose low carbon steel. It has been successfully welded using most all the common practices including gas, resistance, oxyacetylene, and submerged melt welding. It is desirable to investigate the response of AISI 1018 welded joints subjected to impact loading and the effect of the previous fatigue damage on the dynamic response of the welded components.

The aim of this paper is to investigate the effect of previous fatigue-damage on the dynamic tensile behavior of samples obtained from AISI 1018 welded joints by using the split Hopkinson bar apparatus. Different loading rates and previous fatigue damage levels are considered. Quasi-static stress-strain response for different damage levels are evaluated as well. Fatigue damage was introduced on the test specimens by application of cyclic loading under a stress control condition. The response of the welded joints and that of the base material are compared. Next the experimental procedure is described, followed by the results and a discussion of them. The influence of previous fatigue damage on quasi-static and dynamic mechanical properties and failure modes on both materials are analyzed. Finally, conclusions are presented.

2. EXPERIMENTAL PROCEDURE

2.1 Materials, welding process and specimen preparation

In this study, some sets of AISI-1018 steel plates with dimensions 250 × 50 × 6.3 mm were welded using an E5154-B10 (7018) filler metal. The welding process was performed using the shielding metal arc welding (SMAW) technique to butt-weld the two plates of this steel. Figure 1(a) presents a schematic diagram of the welding configuration, in which it can be seen that two plates are welded together with a 2 mm root opening gap and a V-shaped joint groove with 60^o angle. After completion of the welding process, tensile specimens were obtained from the middle of the welded joint by mechanical cut. Tensile specimen dimensions are shown in Figure 1.

2.2 Tension test

Quasi-static mechanical properties of both materials were obtained on a MTS-810 testing machine applying monotonic load at a constant speed of 1 mm/min. Table 1 presents the results obtained for the mechanical properties of damage-free material at room temperature. The yield strength was calculated employing the 0.2% offset method.

2.3 Fatigue tests

Stress-controlled fatigue tests performed on an MTS810 machine allowed the determination of S-N curves applying uniaxial cyclic loading between constant stress limits with stress ratio $R=\sigma_{min}/\sigma_{max}=0.2$. The smooth specimens used had 3.15mm in diameter at center, see Figure 1(b). Cyclic loading with sinusoidal wave form at frequency of 35Hz was applied in air at room temperature. It was possible to induce fatigue damage on the tensile specimens at damage levels of D=0.25, 0.50 and 0.75; where $D=n/N_f$ being n and N_f the applied cycles and the applied cycles to failure, respectively.

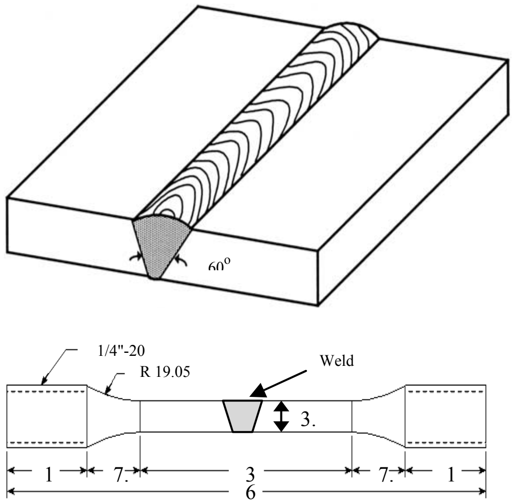

Figure 1. Schematic illustration of the welded joint and specimen used in the quasi-static and dynamic tests. Dimensions in mm.

2.4 Impact test apparatus and dynamic tests

The Hopkinson bar test has been widely accepted to produce strain rates in the order of 102 to 104 s^{-1}. The apparatus consists mainly of an air gun, a projectile, two Hopkinson pressure bars (one incident and one transmitter), a velocity measuring device and recording equipment, for a description of the Hopkinson bar test see for example [2,11,12]. Figure 2 shows an illustration of the bar used on the experiments.

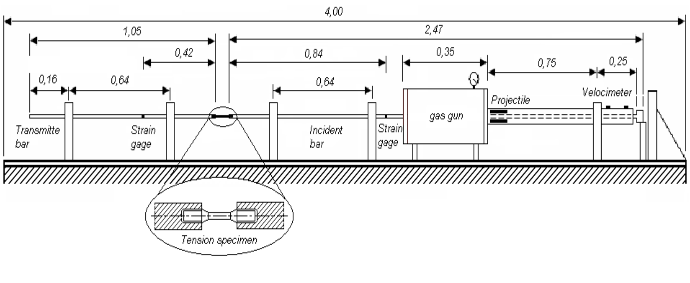

Figure 2. Schematic illustration of the tension Hopkinson bar. Dimensions in mm

3. RESULTS AND DISCUSSION

3.1 Fatigue Tests

Even though fatigue life is needed only under given stress conditions, the complete S-N curves were determined for the base material, the welded specimens with and without heat treatment. Fatigue life, Nf, may be determined from those curves for a given maximum stress σmax at a stress ratio of R =0.2. Fitting the experimental results, the S-N curves may be described by the following Basquin type equation

$$\sigma_{\max} = AN_f^b$$

where σmax in given in MPa. Results for A and b are given in [10].

3.2 Quasi-static tension tests

Quasi-static tension tests were performed on specimens with fatigue damage D=0.25, 0.50, and 0.75. To determine the influence of previous fatigue damage, quasi-static stress-strain curves were determined and shown in Figure 3 with stress-strain curves of damage-free materials included for comparison. From results of Figure 3(a), it is possible to observe no significant effect of previous fatigue damage on the stress-strain response of specimens with as weld condition and D=0.25, 0.50 and 0.75. Young's modulus and yield stress are approximately the same. In other words, the stress train curves for specimens with previous fatigue damage are almost the same, but they are different from those corresponding to the damage free specimens. The stability of quasi-static mechanical properties at different damage levels enhances the behavior of this structural welded steel. It is also worth noting that the yield stress of fatigue damaged specimens is higher than that of damage free specimens. In addition, note that after applying the stress relief heat treatment to the welded joint makes the yield stress decrease approximately 10%.

Table 1. Mechanical properties. Quasi-static condition without damage

	Base Material	Welded Joint
Young's modulus (GPa)	204.7	196.0
Yield stress (MPa)	702.0	455.0
Ultimate stress (MPa)	728.8	587.4

For a summary of the quasi-static mechanical properties see Table 2. From the quasi-static tension tests it is observed that the yield stresses increases about 35% when the damage level changes from D=0 to D=0.75 for specimens with the as weld condition. A similar behavior is exhibited by the ultimate stress, increasing approximately 12%, on the damage level interval from 0 to 0.75.The increase of the yield stress applying cyclic loading is due to the material strain hardening.

It is worth noting that the quasi-static yield stress of the welded joints is lower (around 35%) than that of the base metal.

Table 2. Quasi-static mechanical properties at different damage levels

	Welded joint			
	D=0	0.25	0.50	0.75
Young's Modulus (GPa)	196.0	210.3	214.9	227.9
Yield stress (MPa)	455.0	585.1	600.0	613.6
Ultimate stress (MPa)	587.4	613.1	610.6	655.5

3.3 Dynamic tension tests

Dynamic stress-strain curves of the base metal and welded joint, obtained by using the Hopkinson bar apparatus are shown in Figure 4. Quasi-static stress-strain curves for damage-free materials (base metal and welded joint) are included for comparison. Comparing the dynamic stress strain curves of Figure 4 generated with projectile velocities v=18m/s and v=25m/s we observe no much difference between them; that is, the base metal and the welded joints are not affected significantly by the strain rate. However, it is possible to observe that values for the dynamic yield stress, σy, and the maximum stress, σu, are higher from those values obtained in quasi-static tests, for the base metal and the welded joints as well.

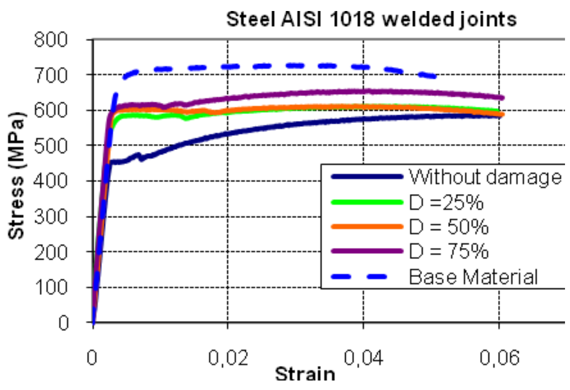

Figure 3. Quasi-static stress-strain curves of the welded joint

The effect of previous fatigue damage, on the dynamic stress strain response, is shown in Figure 5 where different damage levels were considered, the projectile velocity was 25m/s.

3.4 Effect on ductility

To assess the effect of previous fatigue damage and strain rate on ductility of the aluminum and steel samples, one ductility related parameter was evaluated: the percent reduction in area, %RA, given by [13]. This parameter compares the cross-sectional area after fracture, Af, with the original area Ai.

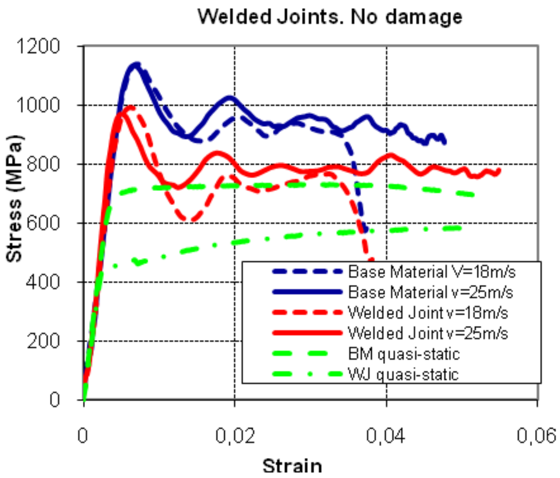

Figure 4. Quasi-static and dynamic stress strain curves of damage free welded joints and base metal at different projectile velocities.

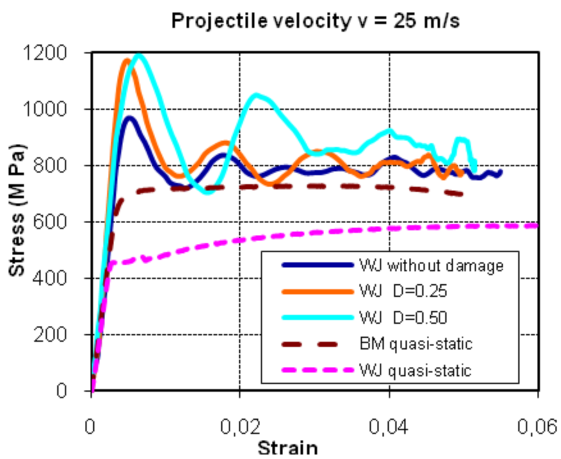

Figure 7. Quasi-static and dynamic stress strain curves of the welded joint and base metal with different damage levels. WJ and BM stand for welded joint and base metal, respectively.

Figure 8 shows the %RA for different damage levels on the welded specimens without stress relief heat treatment tested with a projectile velocity of 25m/s. The percent reduction in area changes (from approximately 48% to 38%) increasing the damage level; while the quasi-static %RA changes from 58% to 50%. Thus, fatigue damage has a detrimental effect on ductility of welded samples in quasi-static and dynamic tension tests. Hence, previous fatigue damage has a detrimental effect on ductility of AISI 1018 steel welded joints even with stress relief heat treatment, mainly on the dynamic loading conditions. This result is due to the strain hardening because of the cyclic loading.

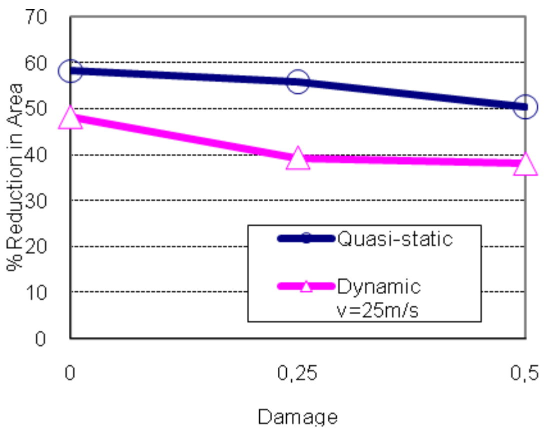

Figure 8. fatigue damage effect on ductility of AISI 1018 steel welded joints. Projectile speed for the dynamic tests v=25m/s, Percent reduction in area %RA

3.5 Failure modes

Figure 7 shows a photograph of a tested specimen showing the welded joint and the fracture surface. Note that the fusion line is oriented about 60^0 with respect to the specimen axis, and the fracture surface has approximately the same orientation.

Figure 13(a) shows the effect of fatigue damage on the failure modes of steel samples on the quasi-static experiments. We may observe that fracture surface orientation changes with the damage level D. For specimens with D=0.25, the fracture surface is about 60^0 from the specimen axis, while the angle is near 90^0 when D=0.75. In addition, note that significant necking is appreciated in all the cases. Damage occurs by void nucleation, growth and coalescence of voids at second phase particles. It is concentrated in regions adjacent to the fracture surface where plastic strains and the associated hydrostatic stresses are highest. This suggests that there is a transition on the steel behavior increasing D. A ductile response is observed at small values of D while a brittle behavior is exhibited by the material at high damage levels.

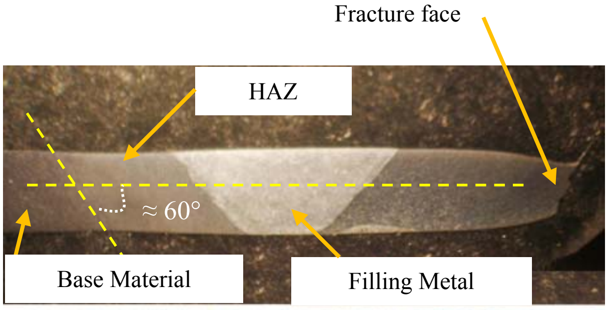

Figure 7. Photograph of a tested specimen showing the welded joint and the fracture surface.

For specimens with D=0, the fracture surface is about 60^0 from the specimen axis, while the angle is near 90^0 when D=0.75, for both specimens with and without heat treatment. In addition, a significant necking is appreciated in all the cases.

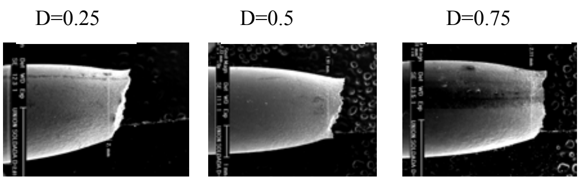

Figure 8. Fracture modes of AISI 1018 steel welded joints at different fatigue levels

4. CONCLUSIONS

The influence of previous fatigue damage on the quasi-static and the dynamic tensile behavior of AISI 1018 steel welded joints have been evaluated. Dynamic tension tests were performed on a Hopkinson bar apparatus.

From the quasi-static tension tests it is observed that the yield stresses increases when the damage level increases as well. A similar behavior is exhibited by the ultimate stress. It is worth noting that the quasi-static yield stress of the welded joints is lower (around 35%) than that of the base metal.

The dynamic experiments show that the yield stress of the welded joints is lower than that of the base metal. The projectile speed does not affect significantly the dynamic response neither of the welded joints nor that of the base metal. The dynamic response of welded specimens without stress relief heat treatment shows that the yield stress increases when increasing the damage level.

From the failure surface analysis of the samples, it is observed that the fracture surface plane was oriented about 60o with respect to the specimen axis for damage-free specimens, while that angle was near 90o when D=0.75. This suggests a transition on the steel behavior when increasing D. A ductile response is observed at small values of D while a brittle behavior is exhibited by the material at high damage levels. This is in agreement with the decrease in %RA when the damage level is increased.

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