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Sensitivity to dynamic strain aging in C–Mn steels

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Abstract

In C–Mn steels and associated welds, the dynamic strain aging (DSA) phenomenon induces an increase in the ultimate tensile strength, which is associated with a ductility drop in the 100–200 °C temperature range (which can be an index of DSA sensitivity). Moreover, in the heat-affected zone of the welds, the sensitivity to DSA, which is microstructure dependent, cannot be directly determined. Therefore, to study the effect of the microstructure on the DSA, internal friction tests combined with tensile tests were performed on various materials and microstructures (resulting from different quenching conditions), exhibiting various DSA sensitivities. For these microstructures, the intensity of DSA, evaluated by the ductility loss, is proportional to the Snœk peak height. Using the internal friction results (Snœk peak and associated cold work peak), the effect of microstructure on the DSA sensitivity can be interpreted in terms of the effect of the dislocation density on the free interstitial content in the lattice.

1. Introduction

In C–Mn steels and associated welds, the dynamic strain aging (DSA) phenomenon induces an increase in the ultimate tensile strength and a ductility loss [1]. In the heat-affected zone (HAZ) of the welds, the different microstructures exhibit different DSA sensitivities. In a previous study [2], tensile tests showed the lower sensitivity of quenched microstructures to DSA, in contrast to the finding in refs. 3 and 4. In the present study, internal friction tests were performed on the same materials with various microstructures, in the −20 to 600 °C temperature range, in order to correlate these results with the different DSA sensitivities revealed by the tensile tests.

2. Materials

The C–Mn steels and welds used in the previous and present study are as follows: material deposited by manual metal arc welding (MMAW), made with a basic coated electrode SAFER MF 48 NUC; AFNOR (French standard) NFA 36205-grade A42 base metal in the normalized condition; AFNOR NFA 36205-grade A48 base metal in various conditions (normalized or water quenched), corresponding to different microstructures (banded ferrite–pearlite or martensite–bainite). These base metals and associated welds are representative of those used in industrial processing, especially from the DSA sensitivity point of view, since the plates represent two extreme steelmaking procedures: the first plate is fully killed with aluminium (A42), whereas the other is semi-killed with silicon (A48). The chemical compositions of these two steels are given in Table 1. The different heat treatments of A48, reported in Table 2, were designed to simulate various microstructures as close as possible to the HAZ microstructures, thus allowing further evaluation of DSA fluctuations in the HAZ. Additional information on materials and microstructures is given in refs. 2 and 5.

3. Experimental procedure

The tensile tests were performed in the temperature range 20–300 °C, with a strain rate of 2.4×10^{-4} s^{-1}. For the weld material and the normalized A42/A48 base metals, the tests were carried out on specimens in the as-welded or normalized state, respectively, or on stress-relieved specimens. Stress relieving was achieved by a post-weld heat treatment (PWHT) in which the specimen was held for 100 min at 600 °C.

Internal friction tests between −20 and 600 °C were performed at 1 Hz frequency on an inverted torsion-pendulum [6] with a heating rate of 130 °C per hour. After *in situ* PWHT, cooling to 20 °C was carried out at the same rate. A second heating treatment between −20 and 600 °C was then performed to test the reversibility of the internal friction plot before and after the PWHT.

TABLE 1. Chemical composition of the materials

	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Al	N2	O2
MMAW	0.049	0.011	0.016	0.356	0.725	0.010	0.011	0.004	0.018	0.057	0.003	0.0093	0.036
A42	0.140	0.0057	0.016	0.225	0.989	0.024	0.021	0.002	<0.003	0.027	0.045	0.0082	0.0006
A48	0.198	0.012	0.0104	0.207	0.769	0.135	0.095	0.025	<0.003	0.273	0.004	0.0083	0.0049

TABLE 2. Heat treatments of A48 steel

Condition	Heat treatment	Microstructure
Normalized	Normalized at 870 °C, air cooled	Banded ferrite–pearlite
A 1050 °C, WQ	Austenized at 1050 °C, water quenched	Martensite–bainite (ferrite)
A 1250 °C, WQ	Austenized at 1250 °C, water quenched	Martensite–bainite (ferrite)

4. Experimental results

4.1. *Tensile tests*

For the materials which are sensitive to DSA, an increase in the ultimate tensile strength (in the temperature range 20–300 °C) associated with a ductility loss (between 100 and 200 °C) is usually observed. Figure 1 shows the ductility loss measured in the different materials, before the stress relieving treatment. Detailed tensile tests results are available in refs. 2 and 5.

The deposited material was found to be sensitive to DSA. This can be attributed to the combination of aluminium with oxygen in the early solidification process. Consequently, aluminium can no longer be effective in trapping free nitrogen. Nevertheless, in this material, the DSA sensitivity is strongly reduced after PWHT.

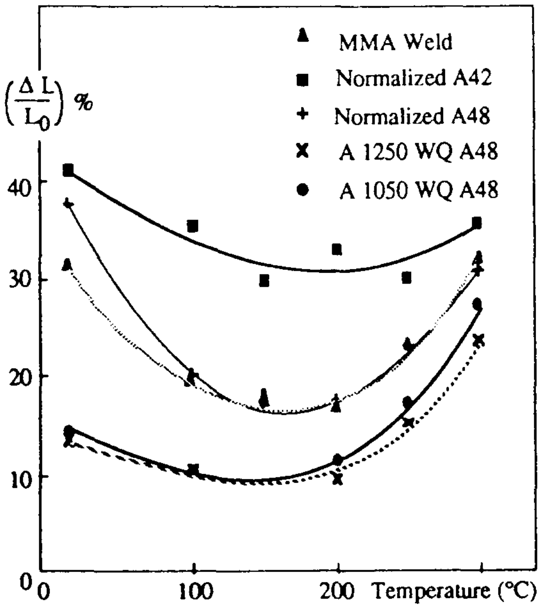

Fig. 1. Total elongation *vs.* temperature.

The normalized A48 steel also appears to be susceptible to DSA, whereas the normalized A42 (aluminium killed steel) is almost insensitive to DSA. This difference between the A42 and A48 steels can be attributed to the difference in aluminium contents as compared with the corresponding total nitrogen contents.

In the austenitized and water-quenched A48 plate, the DSA sensitivity is reduced relative to the normalized state. The harder the microstructure is the less the tensile strength increases with temperature and the smaller is the elongation loss.

4.2. *Internal friction tests*

For these industrial materials, tests show a Snœk peak (SP) associated with a cold work peak (CWP) with different heights. During the first heating (Fig. 2), well-defined asymmetric SP, were observed in MMA weld and normalized A48 steel, whereas the corresponding CWPs maintained a very low level. In contrast, in the quenched A48 steel, the SP was small and the CWP high. Furthermore, in agreement with its non-sensitivity to DSA, the A42 steel showed neither an SP nor a CWP.

The internal friction plots obtained during the second heating (*i.e.* after isothermal holding for 100 min at 600 °C) are given in Fig. 3. These plots are nearly unchanged in the normalized A48 and A42 steels, whereas strong modifications are observed in the other three materials: the SP in the MMA weld and the CWP in the quenched steels have almost disappeared.

5. Discussion

5.1. *Snœk peak*

As discussed by Koiwa [7], the SP asymmetry in these industrial materials comes from the overlapping of the

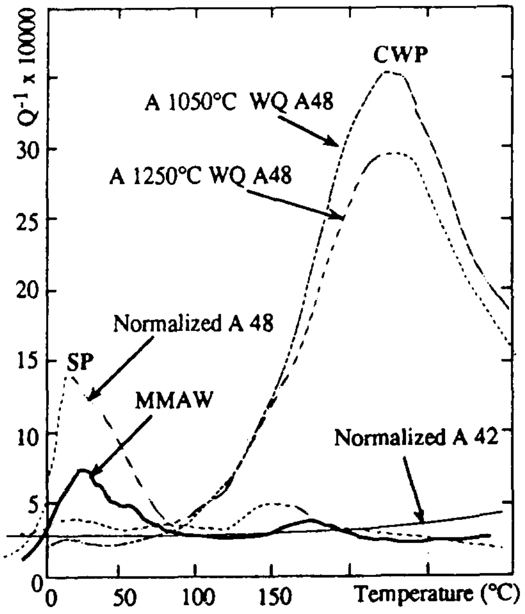

Fig. 2. Internal friction plot (first heating).

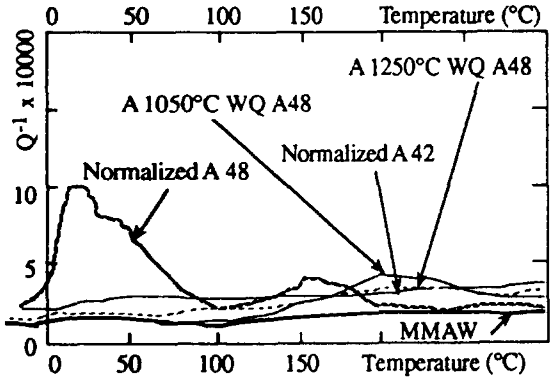

Fig. 3. Internal friction plot (second heating).

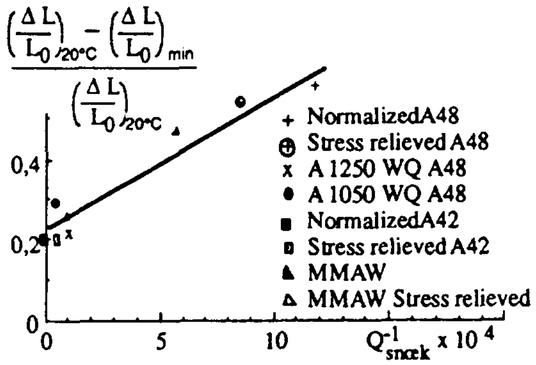

Fig. 4. DSA sensitivity *vs.* Snœk peak height.

C peak and the N peak, and from substitutional atoms (Mn, Al, ...) which broaden the peak.

Considering both internal friction and tensile tests results (Fig. 4), the SP height can be related to

$E = \{(\Delta l/l_0)_{20\,°\mathrm{C}} - (\Delta l/l_0)_{\min}\}(\Delta l/l_0)_{20\,°\mathrm{C}}$

This parameter E, which characterizes the DSA sensitivity, corresponds to the loss in total elongation in the temperature range considered (relative to the total elongation measured at room temperature). As reported in Fig. 4, for all the materials and the thermal treatment considered, a linear relationship between the SP height and DSA sensitivity can be plotted.

5.2. *Cold work peak*

Whatever the physical model considered [8], this CWP is observed when interstitial atoms interact with mobile dislocations.

In agreement, an important CWP is obtained in the quenched A48 steel after aging for several months at room temperature. In this case, the SP height is very small. This result can be interpreted by considering that, after quenching, C and N atoms have been trapped during aging at room temperature by the dislocations resulting from the prior martensitic transformation. Hence, the amount of free C and N interstitial atoms in the lattice is decreased, so explaining the lower DSA sensitivity in these quenched microstructures.

After the *in situ* stress relieving treatment (isothermal holding for 100 min at 600 °C), the CWP has completely disappeared, owing to partial recovery phenomena and to carbide and nitride precipitation, inducing strong dislocation pinning.

6. Conclusions

The DSA sensitivity of C–Mn steels is strongly microstructure dependent. The hardest microstructures consisting of martensite, bainite and ferrite appear to be less sensitive to DSA. This lower sensitivity is attributed to the high dislocation density induced by quenching, and revealed by the CWP height. In this case, C and N dislocation trapping induces a decrease in the amount of free C and N interstitial atoms in the lattice which can be involved in the DSA process.

The DSA intensity, evaluated from the ductility loss, appears to be proportional the SP height. This important result shows that, even for industrial materials, the height of the SP (determined in one test) is a good parameter to check the DSA sensitivity.

This study confirms our previous results, suggesting that the DSA phenomenon is strongly correlated to free C and N interstitials atoms which are present in the lattice.

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