ABSTRACT
The phenomenon of stress-relief cracking or reheat cracking can occur in the Heat Affected Zone (HAZ) of welded joints during Post Weld Heat Treatment (PWHT). The coarse grained region, which results from heating at elevated temperatures in the austenitic field, is the most susceptible to this problem. The present research program aimed at determining, by means of an Acoustic Emission Measurement System (AEMS), the instant of the propagation of reheat cracks during PWHT. The AEMS was fixed to a Modified Implant Test device that allowed the loading of a specimen submitted to thermal cycles similar to those typically experienced by welded components in stress-relief treatments. Tests were performed with this set-up using different load levels for the same thermal cycle and welding condition. Welding was carried-out with the Metal Active Gas process. This study was developed using a High Strength Low Alloy (HSLA) steel commercially produced in Brazil. Tests results have shown that the AEMS is very adequate to monitor the formation and growth of reheat cracking during the Post Weld Heat Treatment.

1. INTRODUCTION
Fusion welding uses thermal energy to cause local fusion between and, as a result, join two or more metallic parts. During this operation, the material adjacent to the fusion zone is submitted to thermal cycles at high temperatures, which results in complex metallurgical transformations and residual stress formation in the region (HAZ). A conventional approach to reduce the built up of residual stresses in the welded joint is to apply a PWHT. This stress-relief treatment consists of heating the welded joint up to an adequate temperature, in which its yield strength is reduced. As the component is kept in this temperature, plastic deformation can occur (dislocation movement), reducing the residual stress level. However, this kind of stress-relief treatment may also deteriorate the mechanical properties of the joint, or even lead to the formation of cracks and, even, to its failure. This phenomenon is known as “reheat cracking” or “stress-relief cracking” (Dhooge & Vinckier, 1993 and Apblett et al., 1990).

The phenomenon of reheat cracking can occur in the HAZ on welds of some HSLA steels during PWHT or during service at high temperature, when the component is submitted to temperatures between 450 and 700°C. Reheat cracks tend to be intergranular and are more commonly found in the coarse-grained region of the HAZ, running usually one or two grains apart from the fusion line (Apblett et al., 1990).

There are a few laboratory test that are proposed in the literature to assess reheat cracking susceptibility of welded joints.
However, none of these tests is standardized. Ideally, specimens for weldability tests should as small as possible and yet representing actual workshop conditions. In the same way, the stress relief heat treatment must reproduce as close as possible the thermal cycles employed in industrial practice what can be hardly achieved in laboratory tests.

The tests known as the Vinckier Method and the Glossop Method demand large specimens. The test plates are welded and submitted to a heat treatment followed by metallographic examination. The results are only qualitative (cracks/no cracks) and a critical stress for cracking is not determined. Tests such as those that employ some relaxation technique can be used to determine the critical stress, but they require a HAZ of great size, which should be obtained by simulation. The results may also not portray the reality. In the same way, creep and hot tensile tests do not represent well real situations. On the other hand, the Modified Implant Test, as proposed here, can be used to obtain quantitatively the stress levels for cracking using actual welding conditions. This methodology presents the following advantages (Tamaki & Suzuki, 1983): (a) - the heat affected zone is produced by actual welding conditions; (b) - several values of residual stress can be simulated by the application of artificial loads; (c) - the relaxation stress during the progress of reheating can be measured; (d) - the test can be representative even when few specimens are used.

A technique very used recently to monitor the propagation of cracks and other flaws in stressed structures is acoustic emission (AE). The AE refers to the transient elastic stress waves generated due to the rapid release of strain energy from a localized source (or sources) within a material. This technology has been extended into widespread applications, such as proof testing and failure mechanism discrimination in aircraft, monitoring the deterioration of composite structures, monitoring of manufacturing processes, etc. (Beattie, 1983 and Liu, 1991).

Hippsley et al. (1988) revealed that, if there was a sudden change in the internal stress field in a material, caused for instance by the propagation of a crack of slip band, then some of the stored elastic energy was dissipated as elastic wave (stress waves). Depending on their amplitude, these could be detected as AE by piezoelectric sensors attached to the surface of the material. Broadly speaking, the amplitude of the detected AE depends on the size and duration of each deformation or fracture event. Furthermore, AE is only emitted when a crack advances, and not when it remains static. Thus careful measurements of the emission activity as a function of time or stress, for instance, can be used to give insights into the dynamics of fracture. Full characterization of each source event has been demonstrated using carefully chosen specimen geometry and broadband detection systems.

The present research program aimed at determining, by means of an Acoustic Emission Measurement System (AEMS), the instant of the propagation of reheat cracks during Post Weld Heat Treatment (PWHT). The AEMS was fixed to a Modified Implant Test equipment that allowed the application of thermal cycles similar to those typically used for stress-relief treatment of welded components.

2. ACOUSTIC EMISSION MEASUREMENT SYSTEM (AEMS)

The AEMS apparatus used in this work to monitor the instant of formation and propagation of reheat cracks during PWHT for stress-relief is constituted of AE sensor; amplifier, Root Mean Square (RMS) voltage converter and date acquisition system. This
configuration is considered to be robust, of low cost, high sensibility and flexibility, and simple assembling by the literature (Liu, 1991).

The output signal from the AE sensor (piezoelectric transducer) was passed through an electronic amplifier (x1000 gain) and processed by a Root Mean Square (RMS.) voltage converter. The RMS. signal pulse was recorded in a microcomputer by an analog/digital conversion card.

The AE sensor is a classification broad band sensor, model WD with a typical operation range of 100-1000kHz. The amplifier works with 40/60 dB and a single BNC connector for power (+28V). The RMS converter was built in the Laboratory of Manufacturing Processes of the DEF/FEM/UNICAMP. This equipment determines the AE energy that is proportional to the integral of the square of the AE sensor output voltage.

As testing could last a long time (from 3 to 8 hours), an event-counting technique that recorded only those data that satisfied certain criteria was devised to save computer memory. In this technique, a computer program controlled the data acquisition card that monitored continuously the output from the AE sensor. This signal was compared with a threshold and only the data points that were above this threshold were stored in files (figure 1 (a) and (b). The computer program allowed the user to define the sampling rate of the data acquisition card, the threshold level and total sampling time. Therefore, by carefully defining the threshold level, it was possible to detect signals from the AE sensor that could be associated with crack propagation and disregard most of those associated with background noise. The output signal that satisfied the used criteria could be reconstructed easily from the stored data files. (Figure 1 (c))

The AEMS used in this work to determine the instant of the propagation of reheat cracking presented the following characteristics: (a) - gain amplifier = 1000 x; (b) - time constant (RMS. voltmeter) = 1 ms; (c) - data acquisition frequency = 2000 Hz; (d) - threshold level = 0.25 V.

3. EXPERIMENTAL PROCEDURE

3.1 MATERIAL

All tests were performed on a commercial grade, quenched and tempered High Strength Low-Alloy Steel. Its mechanical properties are: Tensile strength = 80.0 kgf/mm², Yield strength = 74.9 kgf/mm² and Elongation = 22%. Chemical composition of the material used is given in Tables 1.
Table 1 - Chemical Composition

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</table>

3.2 MECHANICAL TESTING

The conventional Implant Test is largely utilized to assess steel susceptibility to hydrogen cracking. A modified version of this test intended to be used for reheat cracking has been mentioned by some authors (Tamaki & Suzuki, 1983; Tamaki et al., 1993; Ferraresi et al., 1994). The Modified Implant Test, as proposed here, can be used to obtain quantitatively the stress levels and stress relaxation for cracking using the actual welding conditions. (Tamaki & Suzuki, 1983, Tamaki et al, 1993 and Ferrarezi et al, 1994). The test equipment used in this work was designed, built and checked according to Martins (1995). A simplified scheme of the equipment is shown in Figure 2.

3.3 TESTING PROCEDURE

All tests were carried out using automatic GMAW, keeping the same welding conditions, namely: current = 180 A; voltage = 22.5 V; travel speed = 15 cm/min and contact-tip distance = 10 mm (without pre-heating). An AWS E70S-6 wire, 1.2 mm in diameter was used, with CO₂ shielding. During the PWHT, the specimen was heated at 200°C/hour up to the heat treatment temperature (500°C) (Ferrarezi et al, 1994). The temperature was kept in the heat treatment level for four hours (or until fracture occurrence), followed by cooling at a rate of...
approximately 200°C/hour down to room temperature.

4. RESULTS AND DISCUSSION

Data acquisition of temperature, stress level and AEMS reading was simultaneously started at the beginning of the PWHT, when the specimen temperature reached 60°C. The data stored from the AEMS were the time (in seconds) and the level of the signal from the AEMS sensor. Temperature and stress level on the specimen were stored in a computer in intervals of 1 second.

Table 2 presents the results of tests with different values of the initial restraint stress. The values of \( \sigma_i \) and \( \sigma_f \) are related to the modified implant test. The values the \( t_p \), \( P(V) \), \( t_f \), \( NPo \) and \( Npi \) were obtained by processing data obtained by the AEMS. These variables are defined as: \( \sigma_i \) - is the initial value of the restriction stress that was applied just after welding (HAZ temperature of 150°C); \( \sigma_f \) - is the final value of the restriction stress corresponding to the instant of final fracture of the specimen during heat treatment; \( t_p \) - is the value of the time in the instant that the first peak signal from the AEMS was stored; \( P \) - is the value (volts) of the signal from the AEMS stored in the instant \( t_p \); \( t_f \) - is the value of the time in the instant the fracture of the specimen; \( NPo \) - is the number of the points from the AEMS stored in first peak; \( Npi \) - is the number of the peaks from the AEMS stored during the test.

Initial restraint stress (\( \sigma_i \)) was gradually reduced among the tests presented in Table 2 until (trials 11 and 12) the test specimen did not fail and no AEMS signal above the threshold was recorded during the complete PWHT cycle. This stress level was named as the admissible initial restraint stress.

One of the best ways of assessing the material’s susceptibility to reheat cracking seems to be by the value of this admissible initial restriction stress. The lower is this value, the more susceptible to reheat cracking the material can be considered. The admissible initial restriction stress is the largest value of initial restriction stress for which no reheat cracking occurs during the thermal cycle. For the material analyzed, \( \sigma_i \) seems to be close to 25,25 kgf/mm\(^2\) (Table 2). This value is rather lower than the yield strength of this steel (74,9 kgf/mm\(^2\)).

To illustrate and facilitate the understanding of the data showed in Table 2, Figure 3 shows the result of test number 01 of Table 2. This test was started (time = 0) with the furnace at 60°C and with a stress level of 63.13 kgf/mm\(^2\). In the instant of fracture of the specimen, the temperature was 488°C with a stress of 53.88 kgf/mm\(^2\). In this case the specimen failed before the heat treatment temperature (500°C) was reached. The stress curve of Figure 3 indicates that a stress relaxation of 10.25 kgf/mm\(^2\) had occurred before the final fracture of the specimen.

The Figure 4 shows the AE signal (output signal of the RMS voltmeter) for the same previous test in the instant the fracture of the specimen. This figure indicates that, in this trial, two AE peaks (\( NPi = 2 \)) had occurred just before a final large and long peak with a voltage of over 10 V. It is possible to verify that the first peak lasted 12 points (\( NPo = 12 \)) and that the second peak presented 8 data points above the AEMS threshold.

This result (Figure 3 and 4) suggests that the instant of formation (first propagation) of the reheat crack occur in the first peak, with \( P = 1,64 \) V. The second peak indicates the instant of a second propagation of the crack and the rupture of the specimen. For last peak of over 10V indicates the instant the broken specimen contacted the structure of the test equipment.
It is possible to verify in Table 2 that, in tests number 01, 02 and 04, two peaks were registered by the AEMS, in tests number 03 and 05, the AEMS registered just one peak and, in test number 06, 4 peaks. Eight additional tests, that were interrupted at the time $t_i$ of the PWHT thermal cycle, were performed to confirm that the peaks registered by the AEMS indicated the moment of formation and propagation of reheat cracks. In order to confirm those indications the specimens were cutted and polished, observing the presence of cracks. The results were compared with the signals registered by AEMS, and they were coherent. Based on ours experiments we can than affirm that the AEMS is adequate for determination of reheat cracking during the thermal cycle after welds.

Hippsley et al. (1988), who used AE sensors to detect the propagation of high temperature cracks, indicated that the mean time interval during which a crack propagated was approximately 10 ms. The number of points registered in the first peak (NPo) registered by the AEMS varied between 6 of 21 (Tables 2). As the data acquisition time was 0.5 ms, this corresponds to time intervals of 3 to 10.5 ms. This result is, therefore,
compatible with those presented in the literature.

Metallographic examination showed that cracks in the test specimens presented those typical characteristics of reheat cracks mentioned previously. The cracks run along the grain boundaries and parallel to the fusion line, as illustrated in Figure 5.

The results of the Modified Implant Tests can be expressed in a graphical display, in which the temperature and stress level are related to the test time. Figure 5 uses this technique to present the results of the tests of Table 2. The “x” signs on the stress curves of Figure 5 indicate fracture times and stress levels that also correspond to the instant of formation of reheat cracking.

Figure 6 shows the crack initial curve. It can be verified that, as the initial restraint stress is reduced, a longer time is needed for fracture to occur. Particularly, when the restraint stress is sufficiently low, so that the specimens does not crack before about 16000s of testing, the restraint stress tends to remain constant afterwards and no cracks are formed. This demonstrates that, for a heat treatment temperature of 500ºC, reheat cracking has a larger probability to occur in the two first hours of the heat treatment.

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5. CONCLUSION

The AEMS fixed in the Modified Implant Test was an adequate tool to determine the instant of formation and propagation of reheat cracks during of the Post Weld Heat Treatment for stress relief.

The time length of the signal registered by the AEMS and associated to the initiation of reheat cracking varied between 3.5 and 10.0 ms with a mean intensity of the 3.5 V.

For a heat treatment temperature of 500ºC, reheat cracking occurs with higher frequency in the two first hours after the heat treatment temperature is reached.
The testing equipment (sensor and equipment) is versatile and presents an ease operation. This kind of equipment can be utilized before the specification of materials or of welding procedures for applications where PWHT is required. This practice can be an important tool for life assessment of equipment for high temperature operation and for the improvement of this type of equipment.

6. ACKNOWLEDGEMENT

The support of USIMINAS in the specification and characterization of the steels was greatly appreciated. The authors wish also to acknowledge the financial support of the Sao Paulo State Council for Research Development, FAPESP.

7. REFERENCES


