FATIGUE BEHAVIOUR OF VARIOUS STEELS WELDED WITH A STAINLESS STEEL FILLER METAL

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The fatigue properties of welded heterogeneous assemblies currently considered in heavy steel fabrication were investigated, and in particular the welding of high-strength steels using a stainless steel filler metal, and the welding of a construction steel to a stainless steel, with or without buttering.

Plates 12 mm thick were butt or cruciform welded. After characterization of the microstructure and of residual stresses relative to each type of joint, tests were conducted on as-welded, ground (cruciform) joints or flush machined (butt) joints. The characterization of crack initiation sites and the analysis of results made it possible to determine the parameters which appeared to play a dominant role in the fatigue performance of these assemblies.

1 - INTRODUCTION

The welding of crack-sensitive, high-strength steels to each other or of a construction steel to a stainless steel may be convenient, in particular for heavy steel fabrication, for the following reasons :

- Welded joints between high-strength steels allow a saving in manufacturing cost.
- The joining of a stainless steel to a construction steel enables the use of less costly steel elements offering higher mechanical properties in cases where fabricated construction elements not subjected to corrosion need not be in stainless steel.

While the welding conditions for joining such complex metallurgical structures have already been defined (1, 2), their fatigue behaviour has been dealt with only in a few studies (3, 4, 5) on welded joints or stainless steel overlays in the machined condition, and the use of these joints very often is hindered by unfamiliarity with their service behaviour.

It is accordingly the aim of this study :

- to detail certain fatigue properties of two types of joints requiring the use of a stainless-steel filler metal on a non-stainless-steel base metal,

- to show, by the analysis of the results obtained, the parameters having a significant influence on the fatigue performance of such joints, and to propose solutions making it possible to improve the fatigue performance of these joints.

2 - JOINTS INVESTIGATED

2.1 - WELDING OF A HIGH-STRENGTH STEEL

Plates of a high-strength steel (25 NCD 6-5) were joined by welding using a Z6 CND17-11 filler metal. Three types of joints were made :

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- butt joints (K preparation),
- cruciform joints of the K2 type (core carrying primary stress), and cruciform joints of the K4 type (fillet welds carrying load).

2.2 - WELDING OF A STAINLESS STEEL TO A CONSTRUCTION STEEL.

Two types of butt-welded joints (K preparation) were made between a 13 MND 5 construction steel and a Z 6 CN 18-10 stainless steel using the following procedures :

- welding using a Z 6 CND 20-10-3 filler metal, and buttering of construction steel plate with a Z 2 CN 24-13 filler metal and then welding with a Z 2 CN 20-10 filler metal.

The welding sequences performed are shown for each type of joint in Figure 1.

The tensile properties of the steels investigated are given in Table 1.

Table 1 : Mechanical properties of steels investigated.

Steel	YS (MPa)	TS (MPa)	Elongation (%)	Reduction of Area (%)
Z 6 CN 18-10	285	630	74	84
13 MND 5	590	810	16.4	53
25 NCD 6-5	1090	1180	15.6	61

3 - PROPERTIES OF WELDS

3.1 - MACROGEOMETRY

3.1.1 - Purpose of measurements

The shape of the weld bead has a primary influence on the fatigue behaviour of welded joints in the as-welded condition (notch effect). The higher the strength of the base metal, the greater is this influence (6).

3.1.2 - Measurements carried out

The transition angle θ between the weld metal and the base plate, as well as the weld reinforcement height s in the case of butt joints, were measured in several sections of each type of joint. The average values of the results obtained are given in Table 2.

Table 2 - Macrogeometrical characteristics of welds

Type of weld		θ (°)	s (mm)
Z 6 CN 18-10 + 13 MND 5	without buttering	31	2.1
	with buttering	17	1.35
25 NCD 6-5	butt joints	34	2,7
	K2	60	--
	K4	65	--

3.2 - METALLOGRAPHIC CHARACTERIZATION

3.2.1 - Microstructures hardness

* Purpose of characterization. For joints in the as-welded condition, fatigue cracking always initiates at the weld toe. However, post-welding treatment to improve fatigue performance (grinding for example) can lead to crack initiation at metallurgical defects. Similarly, the propagation path may depend on the microstructure. Consequently, the knowledge of the metallographic properties of the weld can facilitate the interpretation of certain results.

* Microstructures. Microstructures were observed in the base metal, the heat affected zones and the weld metals after electrolytic etching for all the stainless steels and nital etching for the other base metals.

For the high-strength steel welds, the structures of the base metal and of the heat affected zone (HAZ) are predominately martensitic. In the weld metal, ferrite is formed in fine needles after the solidification of the austenite. However, near the center of the weld, the ferrite is coalesced because of the annealing effect of the last runs.

For the welds between stainless steel and construction steel, the base stainless steel is essentially austenitic. Some fine bands of ferrite exist in the rolled plate, probably caused by segregation. In the HAZ, the ferrite, in larger proportion than in the base metal, is in the coalesced state. The construction steel is a mixture of pearlite and ferrite. The heat affected zone is bainitic. The weld metal exhibits the same properties as in the high-strength steel joints. The weld metal used for buttering contains less ferrite than the weld metal, because of a difference in the chemical composition of the electrodes used.

* Hardness. Hardness measurements (HV5 or microhardness) were carried out on sections through the weld along the joint profile 1 mm under the skin and in the thickness direction below the weld toe. The results of these measurements are given in Figure 2. In every case, a major increase in hardness was observed in the heat affected zone. For the high-strength steel : $HV_{MAX} = 550 \simeq 1.5 \times HV_{\text{base metal}}$. For welds between construction steel and stainless steel, in the construction steel :

$$HV_{MAX} = 420 \simeq 1.6 \times HV_{\text{base metal}}$$

Beneath the zone of maximum hardness is a slightly softer zone probably resulting from the annealing effect of welding.

3.2.2 - Residual stresses

* Extent of residual stresses. The residual stress field is added algebraically to that of the applied stresses. Knowledge of the residual stress field can :

- as concerns crack initiation, make it possible to determine the influence of residual stresses on the endurance limit of welded joints ;
- as concerns propagation, allow an understanding of certain deviations of the propagation path.

* Measurement conditions. Residual stresses perpendicular to the weld were measured by X rays on a Rigaku Strainflex apparatus. Measurements were carried out at the weld toe and in the base metal on the surface and at different depths after electrolytic polishing and on a section through the weld (at mid thickness, at one-fourth the thickness and under the surface). Measurements in the thickness were preceded by electrolytic polishing to a depth of 0.1 mm so as to eliminate any residual machining stresses. An example of the location of measurement points is given in Figure 3.

* Results. The results are shown in Figure 4. The stress field measured in the thickness is not the one which actually exists in the joint since it has been cut out, but it gives an image of the shape of the real residual stress field. For welds between construction steel and stainless steel, measurements were carried out only in the construction steel.

* Analysis of results. Welds of high-strength steel (Figure 4a). The base metal is under light tension internally. Surface compression is of the order of 400 MPa. These stresses are the result of the heat treatment applied to the plates.

With respect to the base metal, a change of sign in the residual stresses is observed owing to the welding operation.

The fatigue initiation zone (weld toe) is in tension.

* Analysis of results : Welds between stainless steel and construction steel (Figure 4b). The base metal (construction steel) is in light tension at mid thickness and in compression on the surface.

The stresses measured at mid thickness are tensile for welded joints without buttering and compressive for welded joints with buttering. Surface stresses are negligible. Below the surface (0,1 to 0,2 mm) tensile stresses (200 to 300 MPa) are measured.

* Conclusions. Maximum tensile stresses equal to 350 MPa were measured at the weld toe in the fatigue crack initiation zone for welded high-strength steel joints. The relatively low level of the stresses measured with respect to the elastic limit of the material is doubtless related to the low strength of the weld metal.

In the case of welds between stainless steel and construction steel, the stresses measured at the toe of the weld are very small on the construction steel side, but tensile stresses (200 to 300 MPa) are measured below the surface.

4 - TESTS CONDUCTED

4.1 - SPECIMENS

Specimens with a useful width between 50 and 60 mm were cut out of the joints in the as-welded condition. Specimens of cruciform joints of the K2 type in width of specimen : 45 mm) were tested after grinding the weld toe. For butt joints, specimens with a in width of 40 to 50 mm were machined so as to completely level off the weld.

4.2 - TEST CONDITIONS

Test were performed on an electro-hydraulic machine under tension-compression ($R = -1$). The test frequency was chosen so that there was negligible temperature rise in the specimen. It was considered that there would be no failure after 2.10^6 cycles. Tests were stopped at 2.10^6 cycles for specimens not fractured at this life.

4.3 - RESULTS

4.3.1 - Location of failure

* Welds of high-strength steel. For as-welded K2 type joints, the crack initiates at the weld toe and propagates through the HAZ and the base metal perpendicular to the applied stress. The K4 type joints generally exhibited the same type of failure as the K2 joints. Some failures occurred from lack of penetration, with propagation into the weld metal. For ground K2 type joints, cracking initiated at the deepest point of the ground region.

On specimens in the as-welded condition, the crack initiates at the weld toe on either side ; the preparation of the base plate has no influence. On the flush-machined specimens tested (five test), all the failures occurred in the stainless steel filler metal.

* Welds of a stainless steel to a construction steel. On as-welded specimens, cracking initiated at the toe of the weld (or the buttering), always on the side of the construction steel, and propagated through the HAZ and the base metal. On the other hand, on the flush-ground welded joints, the crack initiated and propagated in the stainless steel :

- in the base metal for completely ground joints without buttering ;
- in the base metal or at the buttering-deposited metal interface, or the weld metal-base metal interface for flush-ground joints with buttering.

4.3.2 - Analysis of σ,N data

The test results were analysed by means of a program using the mathematical representation of the Wöhler curve proposed by Bastenaire (7) :

$$N = A \frac{e^{-\left(S-E/B\right)^{c}}}{S-E}$$

The curves obtained correspond to the 50% equiprobability of failure and are presented in Figure 5. The endurance limits σ_D (calculated at 2×10^6 cycles) from the analysis of Bastenaire are given in Table 3.

Table 3 - Endurance limits σ_D

Base materials	Joints investigated		σ_D (MPa)
25 NCD 6-5	as-welded butt joint		70
	K2		60
	K4		50
	Ground K2 joint		120
Z 6 CN 18-10 + 13 MND 5	As-welded butt joint	Without buttering	90
		With buttering	105
	Flush-ground butt joint	Without buttering	(230)
		With buttering	170

For tests of the welds made without buttering of the construction steel to the stainless steel in the flush-ground condition, the high stress levels cause significant temperature rise in the specimens for testing frequencies higher than 1 Hz. All the failures occurred in the stainless steel base metal. The number of tests being too small to establish an endurance limit, this was considered to be equal to that of the stainless steel base metal reported in the literature (8).

For the butt welds of high-strength steel in the flush-ground condition, the number of tests conducted was not sufficient to allow a statistical analysis of the results or even an estimation of the endurance limit. The results obtained are shown in Figure 5.

5 - ANALYSIS OF RESULTS AND CONCLUSIONS

5.1 - WELDS OF HIGH-STRENGTH STEEL

Endurance tests carried out under tension and compression on butt joints and K2 and K4 type welded joints in the as-welded condition led to failures at the weld toe and to endurance limits of 50 MPa (K4 joints) and 60 MPa (K2 joints) and 70 MPa (butt joints). The difference in the endurance limit of cruciform joints can be attributed mainly to the difference in the level of residual welding stresses in the initiation zone (+ 115 MPa for K2 joints and + 180 for K4 joints). The endurance limit of butt joints is higher than that of cruciform joints with high residual welding stresses (+ 160 MPa) : this can be attributed to the geometrical characteristics of the weld. On K2 type welded joints, the grinding of the weld toe doubles the endurance limit. On butt joints, the flush grinding of the weld gives failures in the stainless steel filler metal. No failure has occurred by 2.10^6 cycles in the specimen tested at a stress level of 210 MPa. Our results indicate that the endurance limit of flush ground butt joints is of the same order as that of stainless steel (230 MPa). Thus, the endurance limit of as-welded butt joints can be increased by a factor of approximately three by flush grinding.

These improvements show in a particularly clear manner the high sensitivity of high-strength steel to the stress concentration at the weld toe (the notch effect). The harmful effects can be limited :

- by reducing the level of local stress concentration (optimizing weld profile, grinding or dressing of weld toe, etc.), or

- by modifying the residual stresses at the weld toe (by shot peening, for example).

5.2 - WELDING OF CONSTRUCTION STEEL TO STAINLESS STEEL

Buttering causes an increase of about 10% in the endurance limit of as-welded joint under tension and compression, the presence of buttering leading to a smoother geometrical transition between the weld and the base material.

Flush grinding of the bead produces a significant improvement in the endurance limit : 60% for welded joints with buttering, + 150% for welded joints without buttering. The difference observed between the endurance limit of flush-ground welded joints with an without buttering is due to cracking initiated at slag inclusions, observed in the case of flush-ground welded joints with buttering.

Post-welding treatment on such welded joints (grinding, flush machining, shot peening) can restore the endurance limit of the stainless steel base metal.

ACKNOWLEDGEMENTS

This study was financed by the ECSC under contracts Nos. 7210 KD/312 and 7210 KD/313. The residual stresses were measured by ENSAM (Paris).

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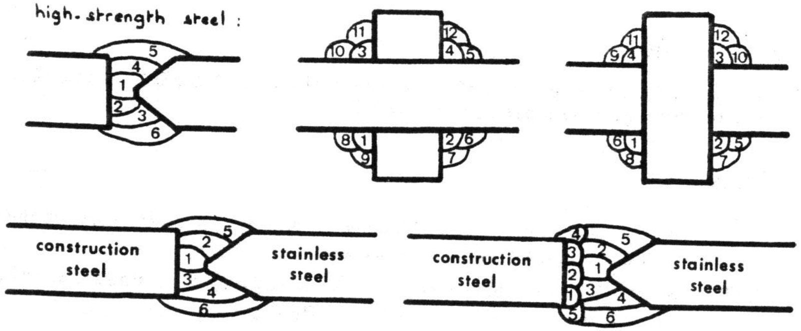

Figure 1 - Preparation of plates and distribution of welding runs.

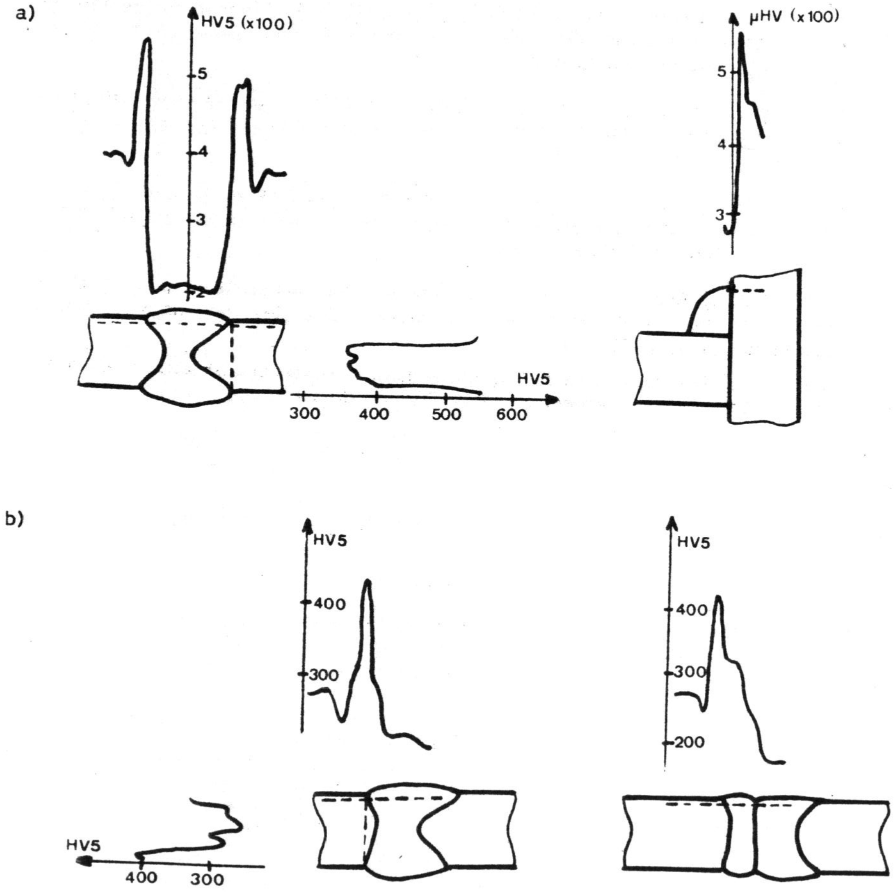

Figure 2 - Results of hardness measurements

a) In 25 NCD 6-5 welds

b) In welds between Z6 CN 18-10 and 13 MND 5.

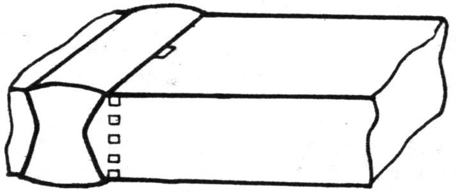

Figure 3 - Location of residual stress measurements.

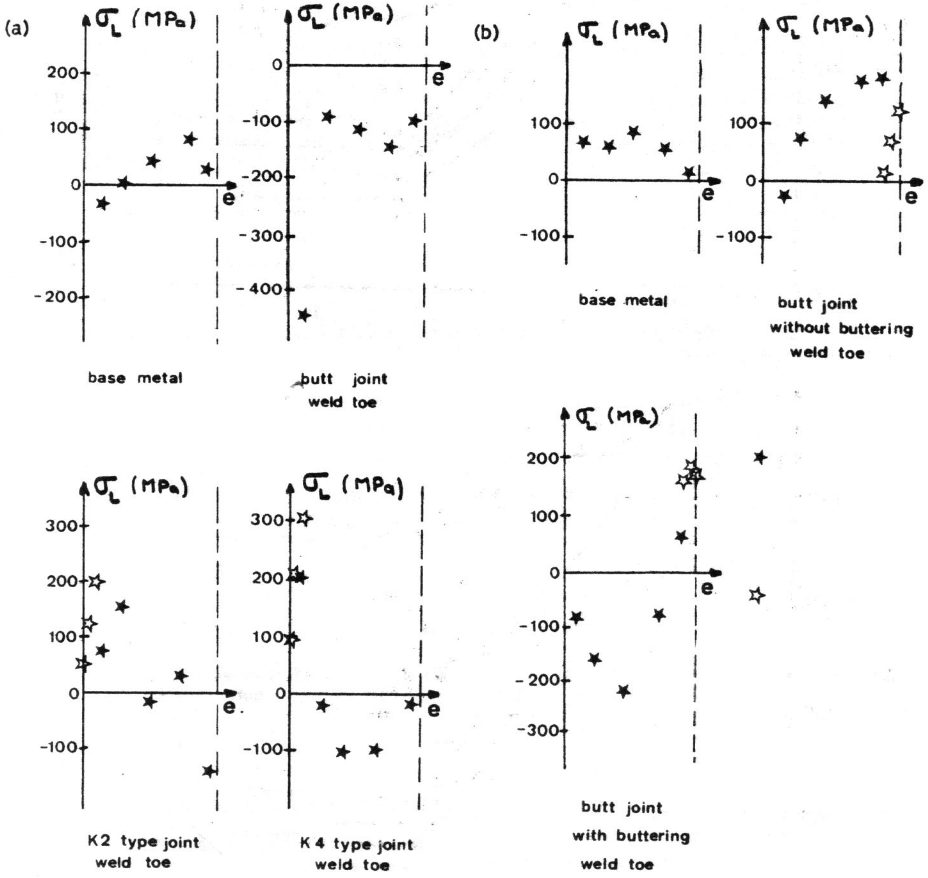

Figure 4 - Residual stresses

a) In 25 NCD 6-5 weld

b) In welds between Z 6 CN 18-10 and 13 MND 5

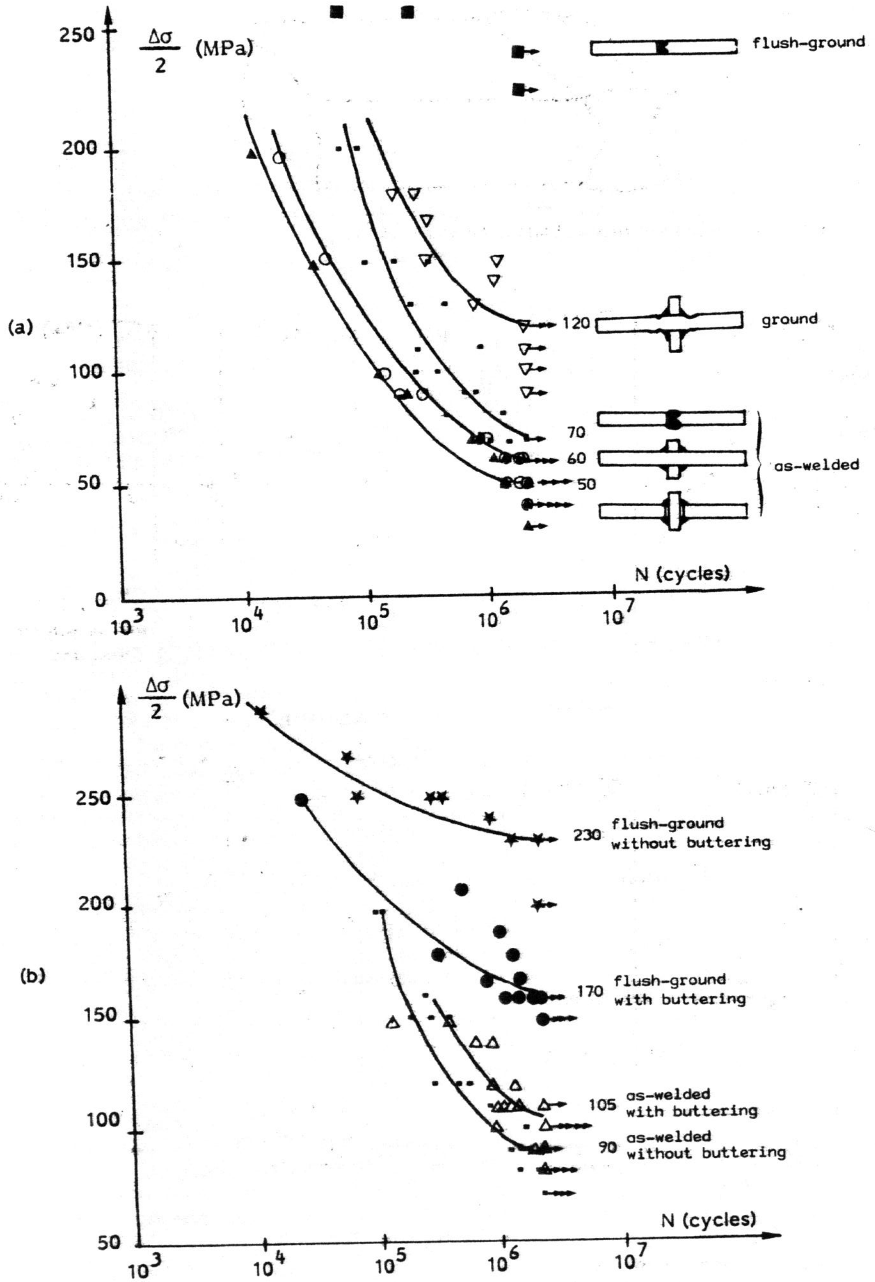

Figure 5 - Wöhler curves

a) Welds of high-strength steel 25 NCD 6-5 b) Welds between stainless steel Z6CN18-10 and construction steel 13MND5