EFFICIENCY OF FATIGUE IMPROVEMENT TECHNIQUES AS A FUNCTION OF THE TYPE OF WELDED JOINT

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Synopsis

The main goal of this paper is to define the efficiency of postweld improvement techniques applied to various fillet welds (T and X types) in a HSS steel (σ_Y = 690 MPa).

The techniques used are postweld heat treatment, shot peening and TIG dressing of the weld toe.

The welded specimens have been cyclically loaded in tension or in plane bending.

The results are compared to those obtained in the as welded condition. To analyse these results, measurements have been carried out to determine : the weld profile and the residual stress at the weld toe.

The effects of these important parameters are discussed.

INTRODUCTION

The advantage of using HSLA steels in the case of structures subjected to cyclic stresses lies in an improvement in the local geometry of the weld toe or in the introduction of residual compressive stresses in the vicinity thereof. Recent bibliographical reviews (1) (2) show the advantage to be gained from using improvement techniques in order to increase the number of cycles needed to initiate a crack, or even to eliminate the conditions required for initiation.

The aim of this study is to compare the behaviour of several types of fillet weld joints which may or may not have undergone improvement treatment.

EXPERIMENTAL CONDITIONS

Material

Type E690 steel, in the quenched and tempered conditions, was used. Tables 1 and 2 give the chemical analysis and mechanical properties of this steel.

Test specimens

Types of joints. Table 3 outlines the types of joints studied, together with the type of loading.

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Type 1: T-joint, (6-pass welding, full penetration weld), subjected to in-plane bending stress

Type 2: T-joint (2 x single pass welding), subjected to bending/tensile stress

Type 3: T-joint (single pass welding on one side only), subjected to in-plane bending stress

Type 4: cruciform joint (4 x single pass welding); the core is subjected to tensile stress (type K2 FEM joint)

Type 5: cruciform joint (full penetration weld, 2 x 6 passes); the stiffeners are subjected to tensile stress (FEM K3 type joint).

Test specimens preparation. The test specimens, whose effective dimensions were 500 mm long x 60 mm wide, were sawn to size. The two of weld ends, as well as the stops and starts, were cropped. Each blank was then milled in order to obtain the final geometry of the test specimens; the edges were ground to avoid premature initiation of a fatigue crack.

Loading conditions

Electrohydraulic fatigue test machines were used (capacity ± 63kN to ± 320 kN). The test frequency was between 10 and 20 Hz.

The tests were generally carried out in tension or in bending cycles (R = 0.1).

Test parameters

The nominal stress range in the plate, $\Delta\sigma$, was calculated at the weld toe. Definition of the fatigue life, N_R, depended on the type of loading, as follows :

Joints subjected to in-plane bending stress (types 1, 2 or 3). Deflection of the test specimen was monitored during the test and the test stopped when the increase in deflection reached 1.5 mm. This criterion corresponded to significant cracking of the test specimen.

Joints subjected to tensile stress (types 4 and 5). In this case, complete failure of the test specimen was adopted as the failure criterion.

Improvement techniques

Three improvement techniques were applied to most of the specimens.

Post weld heat treatment. Some of the test specimens were subjected to heat treatment at a temperature of 560 to 590°C for one hour. The rate of rise and fall of the temperature was fixed at 100°C/hour. Welded joints type 4 were subjected to sand blasting after PWHT.

TIG dressing of the weld toe. In order to obtain a smoother fillet profile and thus decrease the corresponding local stress concentration, TIG dressing, without a filler metal, was applied to a batch of welded test specimens.

After studying the role of the TIG dressing parameters, the following conditions were applied, using a robot, to all of the test specimens concerned:

- Intensity: 200 A
- Voltage: 12.5 V
- Speed: 12 cm/min
- Gas flow rate: 16 l/min
- Energy: 12.5 kJ.

Shot peening. A batch of test specimens was subjected to shot peening of the fillets. The peening conditions were as follows:

. steel balls (diameter: 0.84 mm) Standard MIS 320H
. coverage rate: 200%
. ALMEN intensity: F50-55 A

Measurement of the residual stresses

Many measurements of the field of residual stresses present in the vicinity of the weld toe were carried out, on as welded or improved test specimens before testing. The incremental hole drilling method was used in all cases (3).

This method enables distribution of the residual stresses in the thickness of the material to be determined from an incremental drilling, regardless of the stress profile.

Using the finite element method (CETIM-CASTOR program), it is possible to determine the coefficients which connect the deformation measured at each drilling increment to the residual stresses which exist at the required depth.

The measurements were taken at the weld toe. The centre of the hole was located about 1 mm from the weld toe.

EXPERIMENTAL RESULTS

Fatigue test results

Table 3 shows the following, for each case studied:

- the fatigue strength, $\Delta\sigma$ (the conventional fatigue limit), estimated at 2.10^6 cycles, corresponding to a survival rate of 50%, estimated using the staircase method,

- the site of initiation of the fatigue crack.

Results of residual stress measurements

Table 3 shows, in a large number of cases, the values for σ_{Rx} which correspond respectively to the residual stress perpendicular to the fillet (σ_{RX}) and the principal maximum residual stress (σ_{RI}), evaluated at a depth of 0.1 mm below the surface of the plate.

A comparison of the different profiles obtained was made by determining the development of the maximum principal stress from the surface to a depth of about 1 mm. It is this stress which is taken into account when designing welded structures, generally with transverse stiffeners.

The as-welded state (figure 1) leads to a maximum variation in stress, from one joint to another, of more than 300 MPa, in the first few tenths of a millimeter below the surface. The stresses are generally tensile.

After TIG dressing (figure 2), the residual stress level is always tensile in the vicinity of the surface. It can reach 400 MPa.

In the first few tenths of a millimeter, the stress level after TIG dressing is greater than or equal to that obtained as-welded (figure 3).

In the first few tenths of a millimeter, the difference in results (figure 4) corresponding to test specimens subjected to shot peening, is relatively low in comparison with the other states. The maximum compressive stress is systematically attained at a depth in the vicinity of 0.7 mm. It is between -500 and - 570 MPa.

DISCUSSION OF THE RESULTS

Comparison of the fatigue limit of various as-welded joints

First, it should be noted that there is a considerable discrepancy, in the order of 50%, between the limits obtained, although the joints tested are part of the same family (fillet welds).

Joint 1 produces the highest fatigue limit for two reasons :

- quality of the weld toe: a multipass weld (type 1) results in a better profile than a single pass weld (type 2).

- the type of loading (comparison of types 1 and 5): bending stress exacerbates the effects of the applied stress profile. A discrepancy in the order of 30% has already been found elsewhere (4).

Joint 3 ranks second despite an initiation crack at the root. Its abnormally high level (178 MPa) can be explained by comparison with the level obtained after post weld heat treatment. The presence of residual compressive stresses at the weld root could explain these results.

Joints 2, 4 and 5 have similar characteristics obtained using different welding procedures and types of loading.

Effect of post weld heat treatment

Generally speaking, the effect is only slight, or even negligible (types 1, 2 and 5). The results in the literature on the subject show (5) that post weld heat treatment can improve the fatigue limit for clearly negative values of R (< - 0.25).

The obvious improvement obtained for type 4 is explained by the sand blasting to which the test specimens were subjected after the post weld heat treatment.

Effect of welding conditions

The size of the local fillet between the welding bead and the plate has been presented elsewhere (6). The fillet is directly related to the welding procedure; in particular, as has already been mentioned, multipass welding generally produces a more positive local bead profile than single pass welding (comparison of types 1 and 2).

Systematic measurement of the fillet as proposed by the International Institute of Welding (7) does not however account for the discrepancy in the results.

Role of improvement techniques

TIG Dressing. Table 4 shows the rate of improvement obtained in each case by TIG dressing. This rate, which averages about 65%, corresponds to the lower part of the results in the literature (1) (figure 5a) and seems to indicate that optimization of improvement techniques, which include the initial welding procedure, has not been completely achieved.

From a didactic point of view, application of TIG dressing to the weld toe, in the case of type 3 joints, in which fatigue cracks invariably initiate at the weld root, does not have any significant effect. This result shows that there is no point in applying weld toe improvement techniques to improve a joint in which crack initiation is likely to be from the root.

Shot peening. Shot peening produces an average improvement in the vicinity of 95% in the joints tested (table 4). The results corroborate those in the literature (1) (figure 5b).

Taking the residual stress level into account

In accordance with work published previously (8), in the case of butt welded joints, figures 6a and 6b show two examples of the approach which consists in algebraically adding the residual stresses measured to the mean applied load stress.

In the two cases studied (types 1 and 5), account was taken both the initial residual stresses of the as-welded joints and the residual stresses resulting from the shot peening operation. It was therefore the difference in stress between the initial state and the shot peened state which was taken into consideration when calculating the mean stress to which the weld bead was actually subjected.

The results of tests on the as-welded joints were used to trace the Goodman graphs.

In the case of type 1 joints, the results obtained for the shot peened joint at $R = 0.1$ were translated from $\sigma R = 519 + 23$.

In the case of type 5 joints, $\sigma R = 500 + 90$.

Given the uncertainty of the measurements, the results are encouraging and show the essential role played by residual shot peening stresses on the fatigue strength of the joints studied.

CONCLUSIONS

A study of the fatigue behaviour of various fillet weld joints (cruciform and T-joints) demonstrates the following:

- discrepancies in the order of 50% exist for the fatigue limit; they take into account the quality of the weld (welding procedure), the type of loading (tensile or bending) and the site of the initiation crack (at the root or weld toe),

- under the loading conditions applied ($R = 0.1$), a post weld heat treatment does not seem to have any significant effect,

- application of TIG dressing to the toe weld results in an improvement in the fatigue strength at 2×10^6 cycles, of about 65%,

- shot peening leads to an improvement in the order of 95%,

- the application of improvement techniques is only applicable when there is no risk of a crack being initiated at the root; the better the weld quality, the more effective the improvement technique,

- provided the stress range is small enough ($N > 2.10^6$ cycles), the residual stresses caused by shot peening can be algebraically added to the mean stress of the loading cycle in order to predict the effect on the peening conditions on the fatigue strength.

REFERENCES

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4. Lieurade H.P. Wyseur M. - IRSID Report PE167 (1990)
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6. Lieurade H.P. - Proc. ECF5 Lisbonne, Sept. (1984) pp. 19-48
7. Lieurade H.P., Bignonnet A., Wyseur M., - Welding in the World, vol. 29, n°9/10 (1991), pp. 250-282
8. Lieurade H.P., Tourrade J.C. - Revue générale des Chemins de Fer. Juillet-Août (1985) pp. 357-368

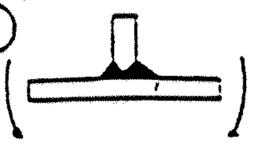
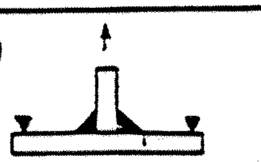
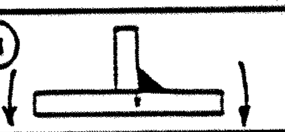
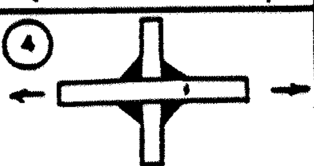
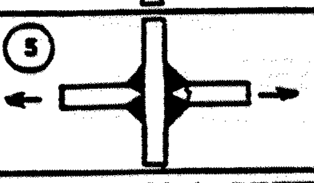
Table 1 : Chemical composition expressed as a percentage of the base metal

Nuance	C	Mn	P	S	Si	Ni	Cr	Mo	Al	Nb	V	B
E690	0,171	1,315	0,013	0,001	0,415	0,189	0,578	0,158	0,032	0,004	0,051	0,0013

Table 2 : Tensile properties (AFNOR E690 steel grade)

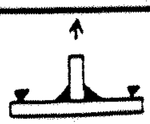
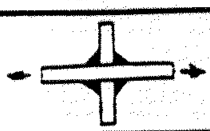
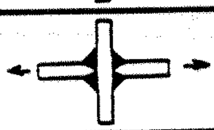
σ_y (MPa)	UTS (MPa)	Elong.	Charpy V at -20°C in transverse direction(J/cm²)
775	845	23	90

Table 3 : Fatigue results (R = 0.1)

Type of joint	Tested condition	$\Delta\sigma_{2.10^6}$ (MPa)	σ_{RX} (MPa)	σ_{RI} (MPa)	Initiation area
1 	AW	207	- 40	+ 23	weld toe
	PWHT	207	- 37	+ 18	
	TD	360			
	SP	392		- 519	
2 	AW	136	- 28	+ 283	weld toe
	PWHT	133			
	TD	(230)	- 48	+ 208	
	SP	288	- 362	- 397	
3 	AW	178	- 45	+ 222	weld root
	PWHT	135			
	T	171			
4 	AW	132	- 39	+ 226	weld toe
	PWHT+SB	223	- 430	- 460	
	TD	218	- 42	+ 214	
	SP	267		- 445	
5 	AW	139	- 2	+ 90	weld toe
	PWHT	151			
	TD	(230)			
	SP	(240)	- 498	- 500	

AW : as welded - PWHT : post weld heat treatment - SB : sand blasting
TD : TIG dressing - SP : shot peening

Table 4 : Improvement due to various post weld treatments

Type of joint	tested condition	Δσ (MPa)	Improvement (%)
(1) 	AW	207	-
	TD	360	74
	S	392	89
(2) 	AW	136	-
	TD	(220)	62
	SP	288	112
(4) 	AW	132	-
	TD	218	65
	SP	267	102
(5) 	AW	139	-
	TD	(230)	58
	SP	(240)	72

AW : as welded - TD : TIG dressing - SP : shot peening

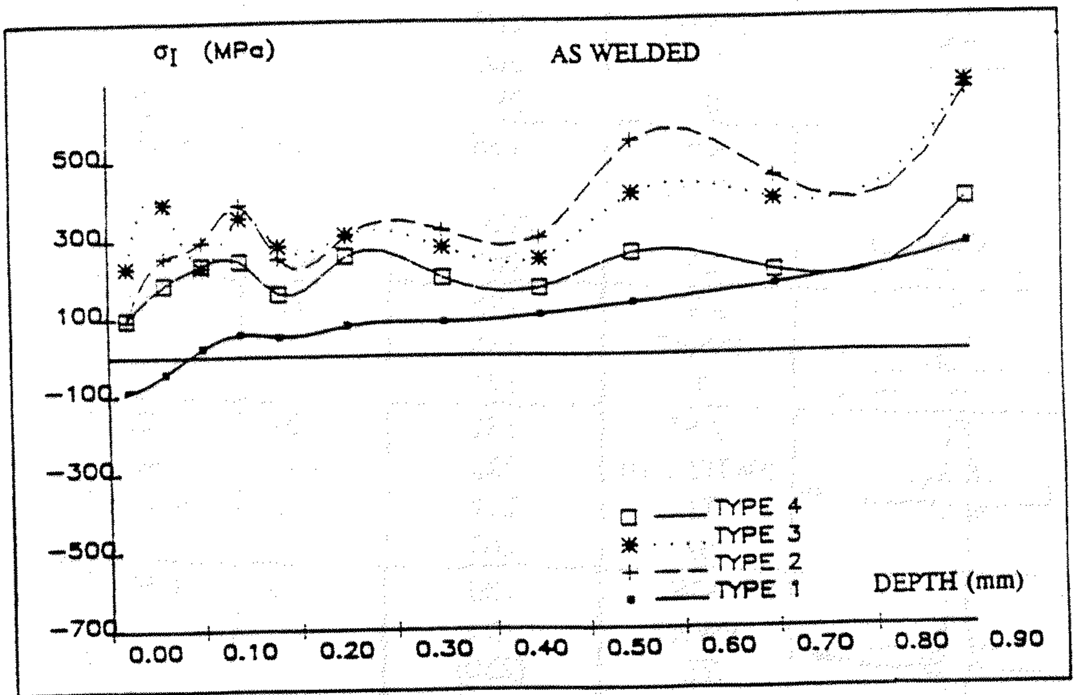


Figure 1 : Residual stress profiles (σ_I) in the as welded conditions

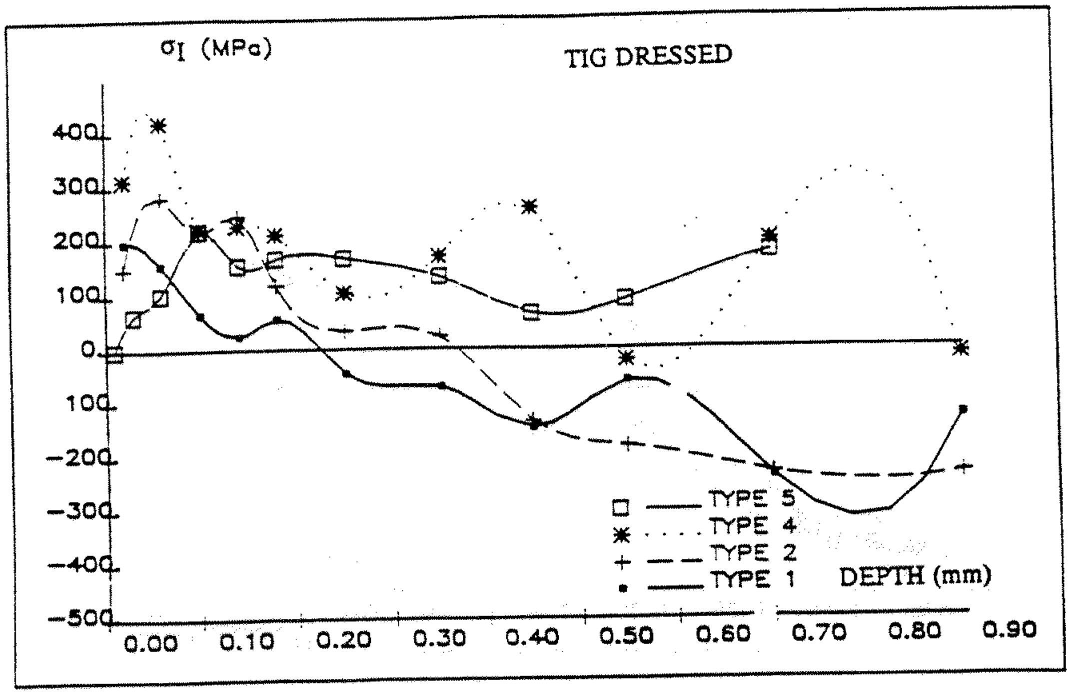


Figure 2 : Residual stress profiles (σ_I) after TIG dressing

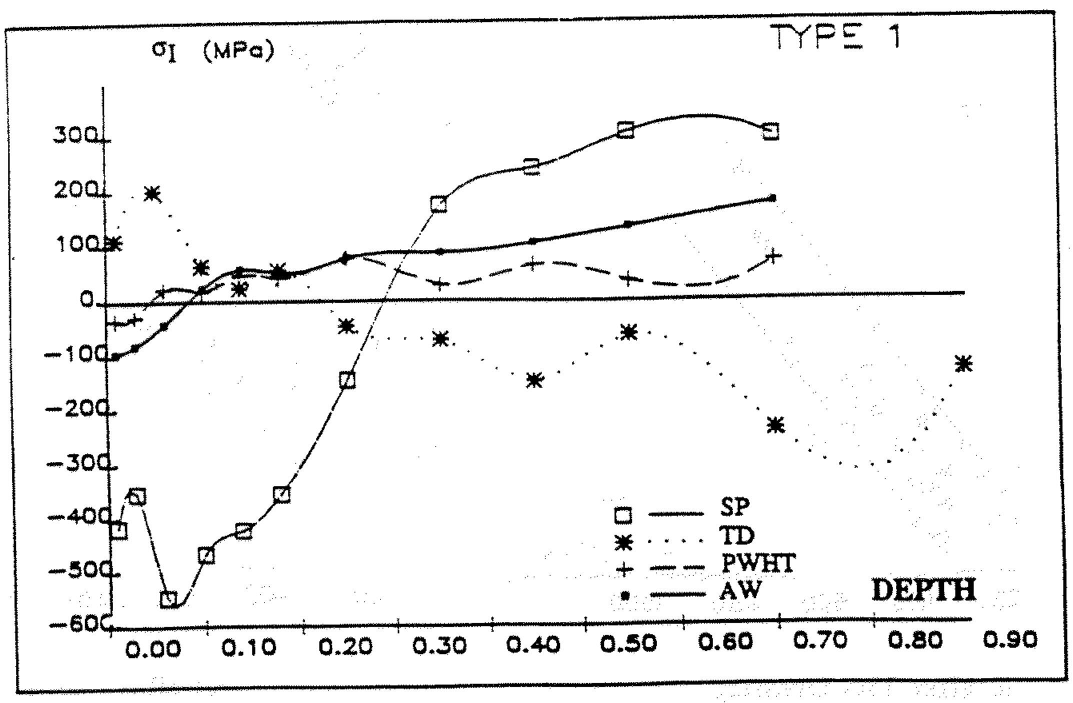


Figure 3 : Welded type 1 - Comparaison on the profiles obtained in various conditions
AW : as welded - PWHT : post weld heat treated - TD : TIG dressed - SP : shot peened

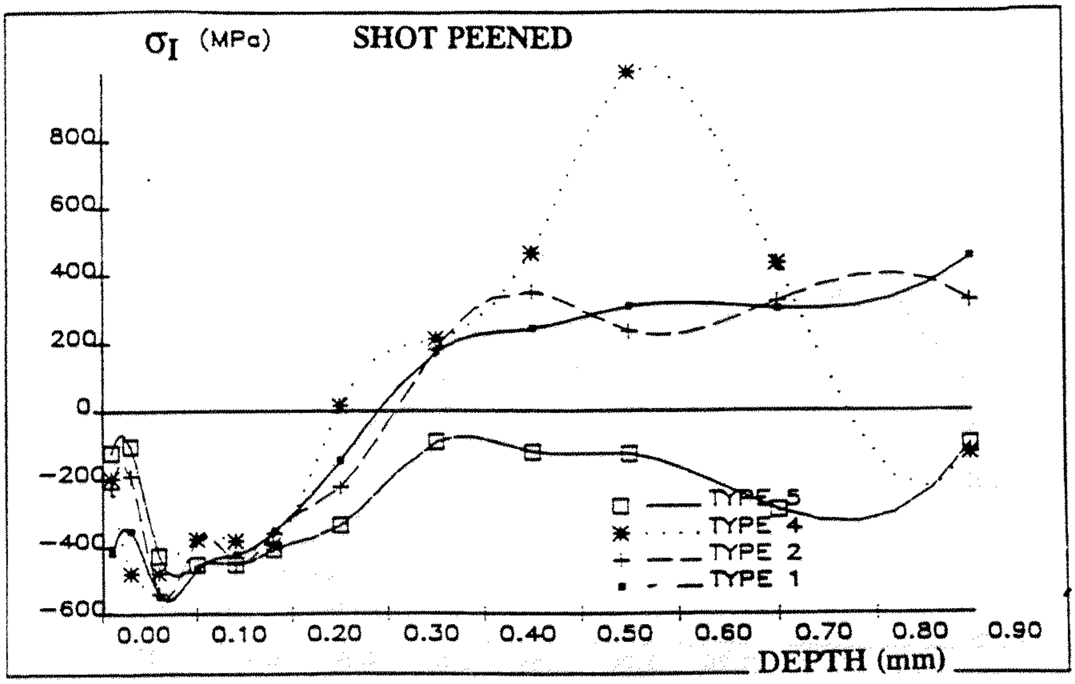
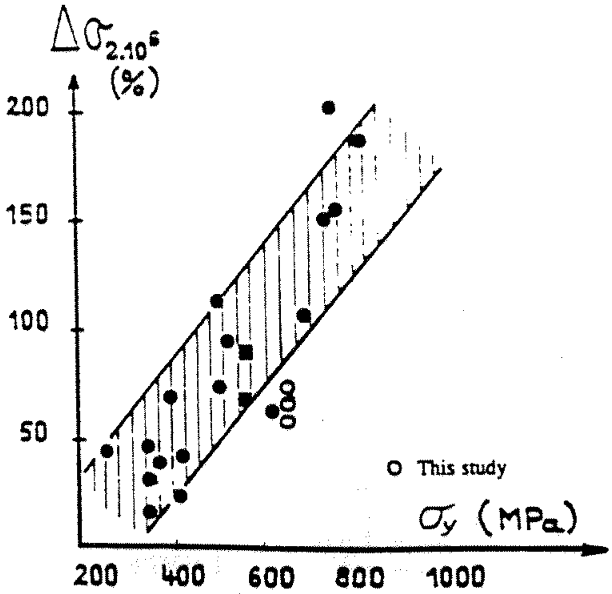
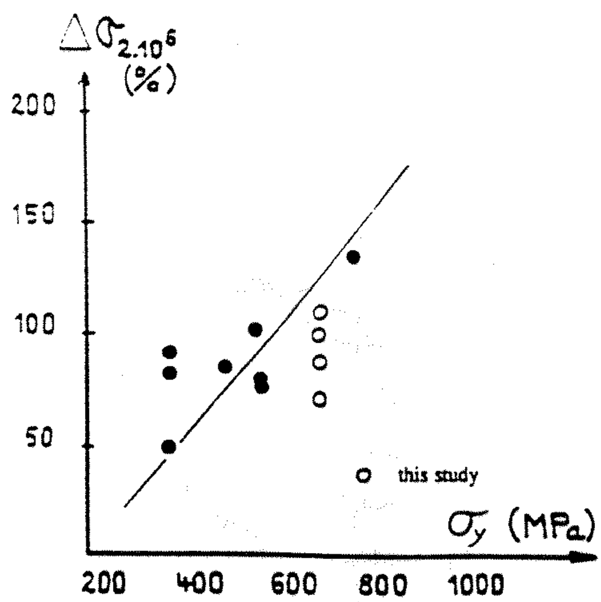


Figure 4 : Residual stress profiles (σ_I) after shot peening



a) after TIG Dressing



b) after shot peeing

Figure 5 : Improvement of the conventional fatigue limit $\Delta\sigma_{2x10^6}$ as a function of σ_Y (fillet welds)

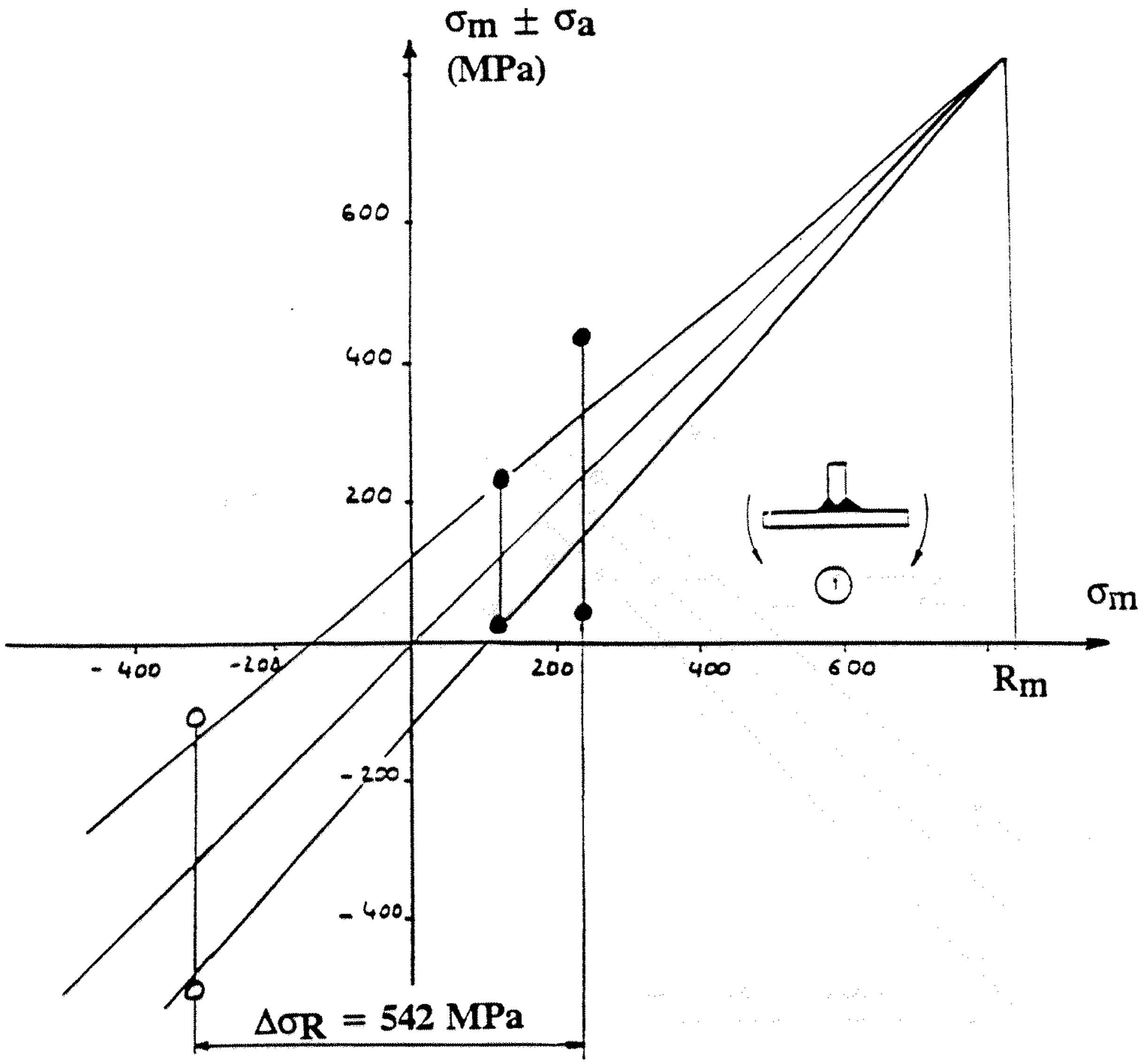


Figure 6a : **Welded joint type 1 - Mean stress effect taking the residual stresses due to shot peening into account**

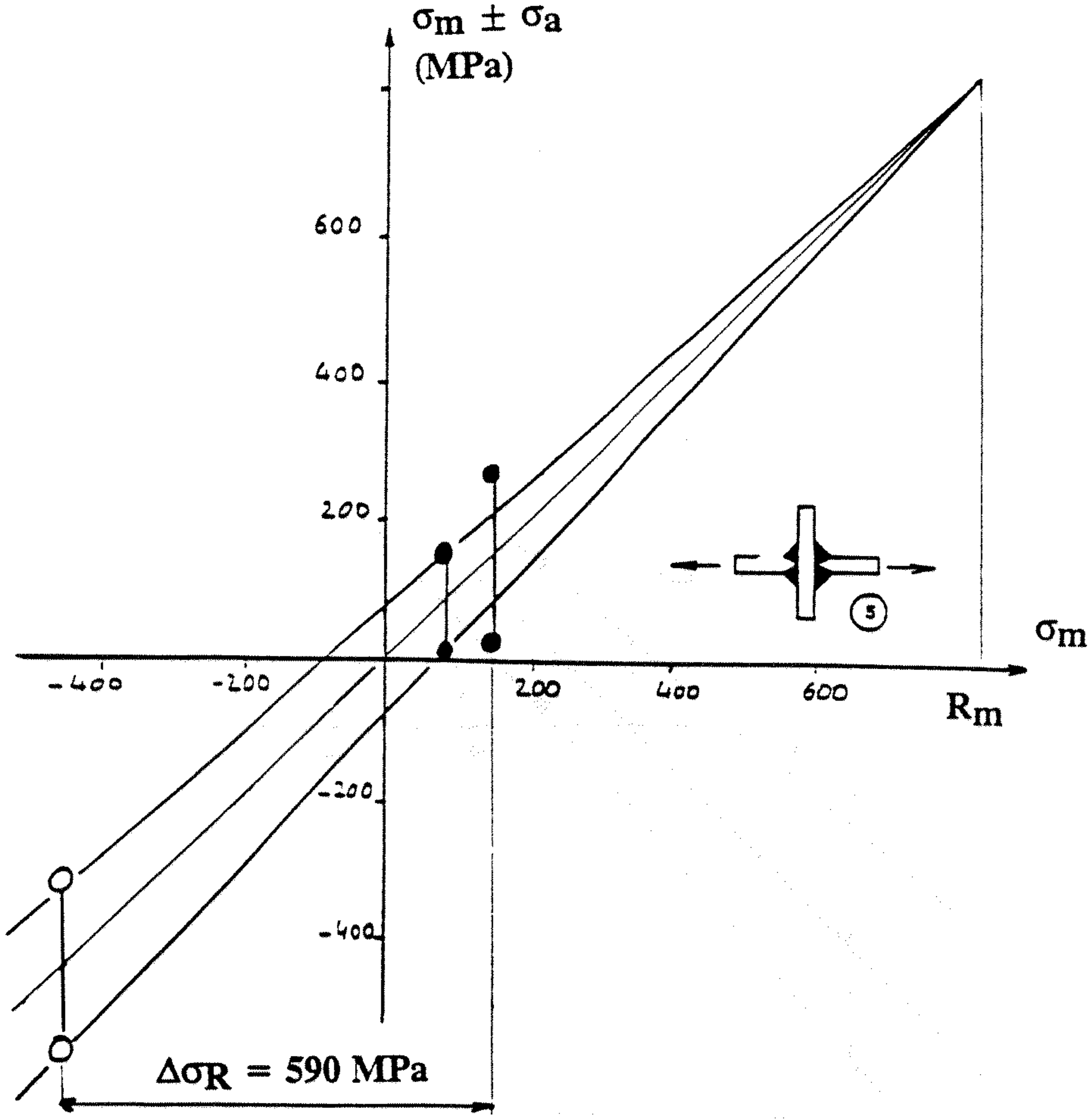


Figure 6b : **Welded joints type 5 - Mean stress effect taking the residual stresses due to shot peening into account**