

# Possibilities for the improvement of the fatigue strength of butt welded joints of high strength structural steels

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**SYNOPSIS** The paper shows that TIG welded or pulsed arc TIG welded joints of high strength steels have the same fatigue strength as manual arc welded and TIG dressed joints. In practice TIG welding of cover and cap passes over underlying MAG welded passes can replace the more time consuming TIG dressing of all weld toes of a totally MAG welded joint. After TIG welding respectively pulsed arc TIG welding and subsequent shot peening the fatigue strength under completely reversed bending surpasses the fatigue strength of the unpeened high strength base material

## 1 INTRODUCTION

It is a well known fact that the fatigue strength of welded joints is appreciably lower than the fatigue strength of the base material - particularly if high strength structural steels are considered. Big efforts have been made to improve the fatigue strength of welded joints for instance by postweld treatments like TIG dressing or shot peening. The intention of this paper is to present pulsed arc TIG welding as a method which produces an extremely flat profile of the weld seam and hence results in a relatively high fatigue strength. As will be shown, these methods result in a considerable improvement of the fatigue strength, for instance of manual arc welded joints. But even after those postweld treatments, welded joints of high strength steels, with an originally conventional weld seam profile, do not reach the fatigue strength of the base material.

This paper further reports on investigations with the aim to check whether other welding techniques which originally produce flat weld seams could be advantageous in improving the fatigue strength of the welded joints of high strength steels. TIG welding and pulsed arc TIG welding are methods which can fulfil the demand for extremely flat profile of the weld seam. Results will be presented which indicate how these welding techniques can be used in practice to get not only an improved fatigue strength of butt welded joints in an economic way but also to reach the fatigue strength of a high strength base material. Observations of crack initiation sites during cyclic loading, measurements of hardness profiles and of residual stress profiles and measurements of residual stresses after cyclic loading help to explain the differences of the fatigue strength of differently welded joints.

## 2 EXPERIMENTAL DETAILS

Two fine-grained structural steels of different yield strength and ultimate strength have been used in the investigations: the widely applied steel St 52-3 in the normalized condition and a steel of the NAXTRA type (German designation

Table 1 shows chemical composition and strength values of both steels. Steel strips of the dimensions 320x80x10 mm have been prepared for welding from rolled sheets (2500x1250x10 mm) by cutting and grinding to remove the rolled skin. The grinding direction as well as the rolling direction were parallel to the short side of the strips, that is the direction which finally becomes the loading direction. The steel strips were given either a V groove preparation or a double V groove preparation (Table 2) parallel to the longer side. For the joining of these strips the following welding techniques have been applied: manual arc welding (MAW), shielded arc welding with a mixed shielding gas (90 % Ar, 5 % O<sub>2</sub>, 5 % CO<sub>2</sub>, MAG), tungsten inert gas welding or pulsed arc tungsten inert gas welding (TIG) and a combination of MAG welding and pulsed arc TIG welding. Table 2 indicates the number of passes and other welding parameters in each case.

During TIG welding of cover or cap passes the volume of the filler material melted was that necessary to fill the groove exactly. In that way an extremely flat profile could be produced, but it was necessary to adjust the wire speed during the whole welding process. This is possible in TIG welding since the wire speed and the heat input are independent from each other. A pulsed arc additionally distributes the weld metal uniformly over the width of the weld seam. Postweld treatments (1) were applied in some cases immediately after welding (TIG dressing) and in other cases (shot peening) after the preparation of the specimens for cyclic loading. The main parameters of postweld treatments are summarized in Table 3.

The specimens for cyclic loading were prepared with a saw cut transverse to the seam of the welded sheets and the final shape shown in Fig. 1a was produced by milling. The longitudinal direction of the specimens, which is transverse to the seam, is the loading direction.

The fatigue tests were performed under completely reversed bending or under tension-compression loading ( $R = -1$ ). The frequency was 25 Hz in each case. In order to get reliable S-N-curves, 12 specimens were tested on two different stress levels in the finite life range and 12 specimens were tested on two different stress levels in the range of infinite life. A limiting number of load alternations of  $2 \times 10^6$  was taken in accordance with the German standard for steels (DIN 50 100 and DIN 15 018). The fatigue strength was calculated by use of the arc  $\sin\sqrt{p}$  transformation. All S-N-diagrams show lines for a fracture probability of 50 %. (Fig. 2 to Fig. 4). Table 5 indicates the fatigue strength values for a fracture probability of 5 %, of 50 % and of 95 % of all investigated states.

The profile of a weld seam could be measured with a profilometer in the case of an extremely flat TIG weld seam or with an inductive displacement pickup in the case of all other weld seams. Fig. 1b includes a representation of important parameters which describe the geometry or shape of a weld seam. These parameters could be evaluated from the profile recordings. Residual stresses due to welding and shot peening have been measured in the surface layers by means of an X-ray technique. For hardness measurements and metallographic investigations the usual methods were applied.

### 3 EXPERIMENTAL RESULTS

#### 3.1 S-N-curves and fatigue strength of differently welded specimens

Fig. 2 shows the S-N-curves of the base materials (state 1) and of specimens of both steels in the following welded states: manual arc welded in the as-welded condition, manual arc welded and TIG dressed, manual arc welded and shot peened. The lines in the diagram indicate a fracture probability of 50 % under completely reversed bending. As usual the fatigue strength of both steels is nearly the same in the as-welded condition (state 2). Differences arise after post-weld treatments. The improvement of the fatigue strength of the steel StE 690 due to TIG dressing (2) is bigger than the corresponding improvement of the fatigue strength of the steel St 52-3 (state 3). An even bigger increase of the fatigue strength of both steels can be produced by shot peening (3) of the welded samples. The fatigue strength of the welded and shot peened specimens of the steel StE 690 (state 4) is particularly high and definitely higher than the fatigue strength of the base material specimens of the steel St 52-3. But neither the postweld treated specimens of the steel St 52-3 (state 4) nor the postweld treated specimens of the steel StE 690 (state 4) did reach the fatigue strength of their own base material.

TIG welding respectively pulsed arc TIG welding was used with the intention to check whether extremely flat final passes would result in a fatigue strength similar to that of TIG dressed specimens. Fig. 3 shows the results. As can be seen TIG welding of the steel St 52-3 (state 5) respectively pulsed arc TIG welding of the steel StE 690 (state 5a) produces practically the same fatigue strength under complete reversed bending as manual arc welding with subsequent TIG dressing of the same steel (state 3). Another

possibility is to apply the TIG process only for the cover pass and the cap pass, which determine essentially the fatigue strength of the welded joint, and to use a more efficient technique like manual arc welding or MAG welding for the root and intermediate passes. A comparison of the S-N-curves for state 6 (MAG welded and subsequently TIG dressed) and for state 5b (first and second pass MAG welded, cover and cap pass TIG welded) indicates that nearly the same fatigue strength under tension-compression loading is produced with both weld methods. The economic advantage of a TIG welded cover and cap pass compared with TIG dressing of all weld toes will be discussed later on.

An interesting question is whether a combination of TIG welding of an extremely flat cover and cap pass with shot peening can offer an additional beneficial effect on the fatigue strength. Fig. 4 compares S-N-curves of base material specimens, of TIG welded respectively pulsed arc TIG welded specimens (state 5) and of TIG welded or pulsed arc TIG welded and subsequently shot peened specimens (state 7) of both steels. It is of practical importance to note that after TIG welding and subsequent shot peening the fatigue strength under completely reversed bending surpasses the fatigue strength of the unpeened base material in both cases considerably. That means, that the combination of an advanced welding technique, which produces extremely flat weld seam profiles, with the benefits of shot peening offers the possibility that butt welded joints get at least the same fatigue strength as the base material.

#### 3.2 Parameters of the weld seam profile, hardness values and residual stresses

The measured values of the parameters which describe the profile of the weld seam help to explain the differences of the S-N-curves of differently welded joints. Detailed observations of crack initiation sites, hardness and residual stress measurements offer also useful information.

As parameters of the weld seam profile of manual arc welded joints are listed in Table 4 the width of the seam, the reinforcement angle and the radius and depth of the penetration notches. Each value is the mean of 24 single values. Fig. 6 demonstrates very clearly the extremely flat profile of pulsed arc TIG welded joints of the steel StE 690.

Fig. 5 indicates a hardness distribution and residual stress distributions versus distance from the surface of manual arc welded and shot peened specimens of the steel StE 690. Fig. 7 represents residual stress distributions on the surface of a pulsed arc TIG welded specimen in the as-welded condition and after  $10^3$  respectively  $10^6$  load cycles.

### 4 DISCUSSION

The differences of the S-N-curve of differently welded joints are discussed in the following on the basis of the measured weld seam profiles, the observed crack initiation sites and the measured hardness values and residual stress distributions.

The manual arc welded specimens include sharp and deep undercuts. Therefore the fatigue strength of these joints is much lower than that of the base material and all fatigue cracks started at the weld toes, either beside the cover pass or beside the cap pass. In most cases a steeper reinforcement angle or a smaller notch radius or a bigger notch depth - up to 300  $\mu\text{m}$  - than listed as mean value in Table 4 could be detected exactly on the crack initiation sites by careful observations. In some cases fatigue cracks started obviously on weld spatters or on scratches due to grinding on the root side.

TIG dressing removes the undercuts of manual arc welded joints nearly completely. Thus the fatigue strength after TIG dressing is improved as a consequence of lowering of the stress concentration at the weld toe. As can be seen in Table 4 the reinforcement angle as well as the notch radius is definitely enhanced due to TIG dressing. According to the change of the weld seam profile other crack initiation sites have been found after TIG dressing. In TIG dressed specimens of the steel St 52-3 all crack initiation sites were found in the base material. Nevertheless the TIG dressed specimens did not reach the fatigue strength of the base material. The reason for this was small surface defects such as weld spatter or scratches due to grinding. Obviously such defects acted as crack starters and lowered the fatigue strength. In TIG dressed specimens of the steel StE 690 only 5 % of cracks started in the base material. 26 % of cracks originated within the transition zone between weld metal and TIG dressed zone and 53 % of cracks directly within the TIG dressed zone. Only 16 % of cracks had their origin within the transition from the TIG dressed zone to the base material. This at least confirms that TIG dressing lowers the stress concentration at the transition from the base material to the zones of melted metal. A reason why more than 50 % of cracks started directly within the TIG dressed zone could not be found from the parameters of the weld seam profile. Scanning electron micrographs of fracture surfaces revealed the reason. Close to the crack initiation points nonmetallic inclusions could be detected. It has to be assumed that very small remains of the weld slag had been deposited near the surface of the weld toe and that these inclusions acted as stress raisers within the TIG dressed zone.

The weld seam profile was not altered due to shot peening. Therefore - with only a few exceptions - all fatigue cracks started at the weld toe of the manual arc welded and shot peened specimens. Consequently the improvement of the fatigue strength due to shot peening has to be attributed to the hardening of surface layers and to the creation of compressive residual stresses in surface layers. The hardness profile of a manual arc welded and shot peened specimen of the steel StE 690 confirms the hardening effect of the shot peening treatment (Fig. 5). The hardness in the very surface of the heat affected zone is 100 HV higher than the hardness of deeper layers. In comparison welded joints of the steel St 52-3 showed an even bigger increment of surface hardness after shot peening. The residual stress profiles in Fig. 5 indicate rather big magnitudes of

compressive residual stresses on the surface and in layers close to the surface as a consequence of shot peening. The somewhat bigger magnitudes of the compressive residual stresses in the heat affected zone (HAZ) can be explained by the higher hardness in the HAZ compared with the base material. According to (4) compressive residual stresses of the observed magnitude, which are rather uniformly distributed on the surface, improve the fatigue strength of steels with the ultimate strength considered here. But with this ultimate strength level the main part of the fatigue strength improvement due to shot peening is a consequence of surface hardening (4).

TIG welded or pulsed arc TIG welded specimens showed relatively high fatigue strength identical, or comparable, to the fatigue strength of TIG dressed joints. The result is a consequence of the extremely flat weld seam profile (Fig. 6) which can be produced if in TIG welding or pulsed arc TIG welding the wire speed is adjusted continuously. The reinforcement angle of TIG welded seams is comparable to that of TIG dressed seams. The toe radius was smaller after TIG welding than after TIG dressing, but the effect of the notch can be nearly the same because the height of the weld seam was lower after TIG welding than after manual arc welding or MAG welding. In the lower finite life range all cracks of the pulsed arc TIG welded steel StE 690 and most of the cracks of the TIG welded steel St 52-3 started at the weld toe. In addition it is remarkable that in many cases small nonmetallic inclusions could be observed in the surface layers of the weld toe. These inclusions can also act as stress raisers.

Investigations on the possible influence of welding residual stresses on the fatigue strength have been performed in the TIG welded state and in the TIG dressed state. As an example Fig. 7 indicates a distribution of surface residual stresses after pulsed arc TIG welding of the steel StE 690. This distribution on the side of the cap pass includes rather high tensile residual stresses in the zone which is sensitive to fatigue cracks. The residual stresses have been measured after  $10^3$  and again after  $10^6$  cycles of the fatigue test. It can be seen that after  $10^3$  cycles the maximum magnitudes of the residual stresses are already considerably lowered. After continued cyclic loading until  $10^6$  cycles another, but smaller relief of tensile residual stresses has been observed. In view of the small magnitudes of the remaining residual stresses one must assume that welding residual stresses cannot have a pronounced influence on the fatigue strength of the investigated specimen (5,6). In other cases only small reduction of tensile residual stresses in zones with an enhanced hardness was observed. Even then fatigue crack initiation could not be detected in the zones with high tensile residual stresses, but partly in zones with small compressive residual stresses. Altogether one can conclude that in the case of butt welded specimens with a seam transversely to the load stress the influence of welding residual stresses is at most weak compared with the influence of notches at the weld toe.

An important result is that after TIG welding or pulsed arc TIG welding and subsequent shot peening the fatigue strength under completely reversed bending surpasses the fatigue strength of the base material. Shot peening is obviously capable of compensating for the relatively weak notch effect of extremely flat weld seam profiles. In accordance with that the crack initiation sites were displaced into the base material - in specimens of the steel St 52-3 completely and in specimens of the steel StE 690 mostly.

If one compares the fatigue strength of welded specimens of the steel St 52-3 with that of the steel StE 690 one can summarize the results in the following way. Despite its much higher yield strength and ultimate strength the fatigue strength of the steel StE 690 in the as-welded state is only little higher than the corresponding values of the steel St 52-3. This well known fact results from the more pronounced notch sensitivity of the steel with the higher ultimate strength. (Careful investigations have confirmed that no differences of significance existed between the weld seam profiles of both steels). As a consequence any lowering of the notch effect of the weld seam profile improves the fatigue strength of the steel StE 690 more than the fatigue strength of the steel St 52-3. This can be seen clearly if one compares the S-N-curves of the TIG dressed specimens or of the TIG welded specimens of both steels in Fig. 2 and in Fig. 4. Shot peening also affects the fatigue strength of butt welded joints of the steel StE 690 more than the fatigue strength of butt welded joints of the steel St 52-3. In that way even the especially high fatigue strength of the StE 690 base material can be reached or surpassed if an advanced welding technique which produces extremely flat weld seam profiles is combined with shot peening.

#### ACKNOWLEDGEMENTS

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Table 1 Chemical composition and strength values

	Chemical composition [Wt %]								Yield strength [N/mm <sup>2</sup> ]	Ultimate strength [N/mm <sup>2</sup> ]
	C	Si	Mn	Cr	Mo	Al	Zr	Fe		
St 52-3	0.154	0.34	1.41	0.03	--	0.042	--	98	400	526
StE 690	0.175	0.62	0.87	0.64	0.27	0.035	0.08	97	722	800

Table 2 Welding procedure

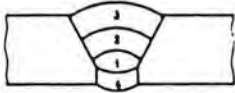
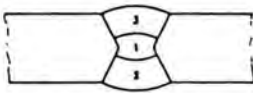

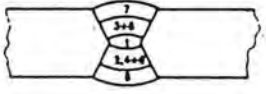

	MAW (2)				MAG (6)				TIG (5+5a)					MAG [1 <sup>a</sup> - 2 <sup>a</sup> pass] (5b) TIG [3 <sup>a</sup> - 4 <sup>a</sup> pass]				
	Pass	Current [A]	Arc voltage [V]	Heat input [kJ/cm]	Pass	Current [A]	Arc voltage [V]	Heat input [kJ/cm]	Pass	Base current [A]	Pulsed current [A]	Arc voltage [V]	Heat input [kJ/cm]	Pass	Base current [A]	Pulsed current [A]	Arc voltage [V]	Heat input [kJ/cm]
St 52-3	1	75	21.0	9.5					1	170		12.0	12.2					
	2	180	24.0	15.4					2-6	200		12.0	14.4					
	3	180	24.0	15.4					7	200		12.0	14.4					
	4	75	21.0	9.5					8	200		12.0	14.4					
StE 690 Preheating temperature: 150 °C	1	100	22.0	10.2	1	140	20.0	8.5	1	135		10.5	8.5	1	140		20.0	8.5
	2	110	22.5	14.9	2	180	22.0	12.0	2-6	185		10.5	11.7	2	140		20.0	8.5
	3	110	22.5	14.9	3	180	22.0	12.0	7	150	220	10.5	11.7	3	150	220	10.0	11.1
	4	100	22.0	10.2					8	150	220	10.5	11.7	4	150	220	10.0	11.1
									 (5)  (5a)									

Table 3 Parameters of post-weld treatments

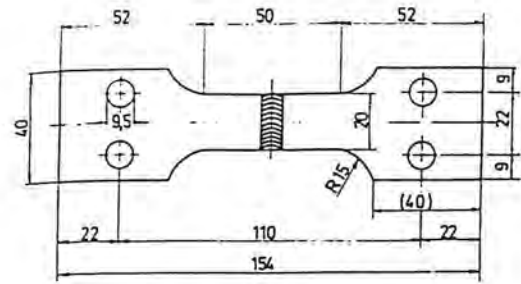
		St 52-3	StE 690	
TIG dressing (3+6)	Base current [A]	110	110	
	Pulsed current [A]	250	250	
	Arc voltage [V]	10	10	
	Heat input [kJ/cm]	10.8	10.8	
Shot peening (4+7)			1.	2.
	Shot	S230	S230	Glass
	Peening pressure [bar]	4	4	4
	Coverage [%]	100	200	100
	Almen intensity [mm]	0.3 A	0.4 A	0.2 N

Table 4 Parameters of weld profiles of manual arc welded specimens and manual arc welded and tungsten inert gas welding (TIG) dressed specimens

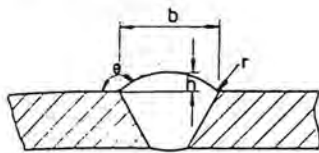
		weld width [mm]	reinforcement angle [degree]	toe radius [mm]	depth of undercut [µm]
St 52-3	MAW cover pass	12.5 ± 0.8	159.3 ± 5.6	3.5 ± 1.9	26.5 ± 28.1
	MAW TIG dressed cover pass	19.0 ± 0.6	173.7 ± 3.1	17.2 ± 8.4	0.0 ± 0.0
	MAW cap pass	7.7 ± 0.5	152.5 ± 7.7	3.0 ± 2.0	36.2 ± 5.5
	MAW TIG dressed cap pass	15.6 ± 0.5	174.6 ± 2.1	18.7 ± 9.5	0.4 ± 2.1
StE 690	MAW cover pass	13.9 ± 0.7	162.2 ± 5.6	4.9 ± 3.1	42.0 ± 44.0
	MAW TIG dressed cover pass	23.2 ± 0.3	175.3 ± 1.4	39.3 ± 17.7	6.1 ± 10.0
	MAW cap pass	7.8 ± 0.5	159.5 ± 6.3	6.4 ± 3.3	30.7 ± 39.2
	MAW TIG dressed cap pass	16.4 ± 0.6	174.4 ± 2.8	15.0 ± 7.8	4.5 ± 9.0

Table 5 Fatigue strength values for fracture probabilities of 5 per cent, of 50 per cent and of 95 per cent of all investigated states

state	St 52-3			StE 690		
	fatigue strength for a fracture probability of					
	5%	50%	95%	5%	50%	95%
1	257	290	322	325	360	395
2	168	185	202	157	190	226
3	235	266	287	233	300	367
4	266	278	290	297	330	363
5	230	260	290	245	266	288
5a	--	--	--	288	305	322
5b	--	--	--	164	210	255
6	--	--	--	172	227	286
7	302	315	325	383	404	429



a)



b)

Fig 1 Specimen size (dimensions in mm) and parameters of the weld profile

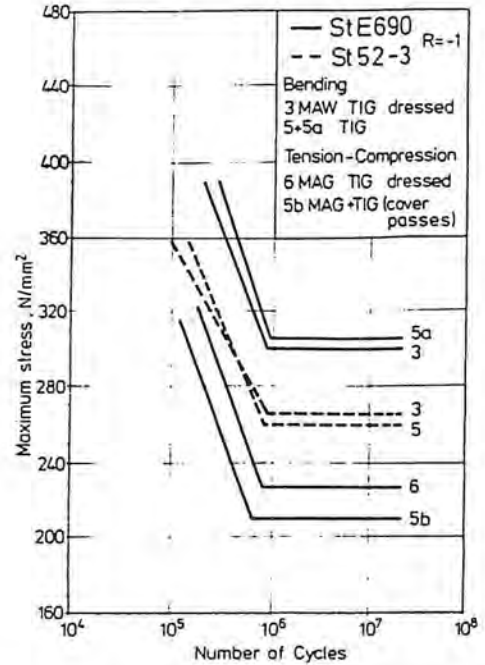


Fig 3 S-N curves of TIG dressed and TIG welded specimens

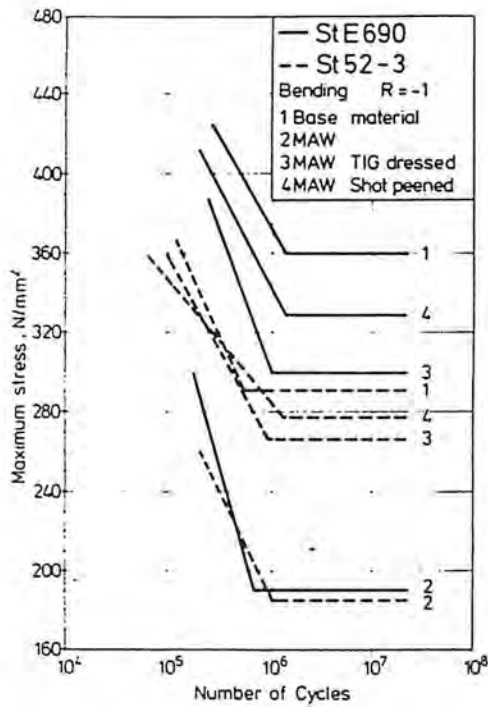


Fig 2 S-N curves of the base material, of manual arc welded specimens and of post-weld treated specimens

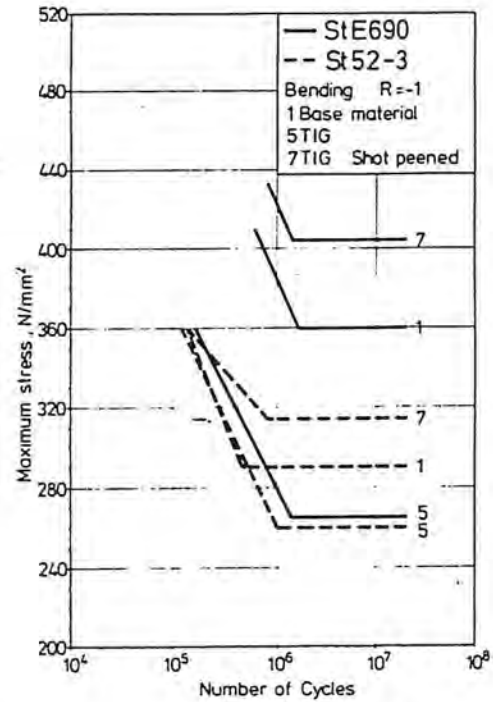


Fig 4 S-N curves of the base material, of TIG welded and of TIG welded and shot peened specimens

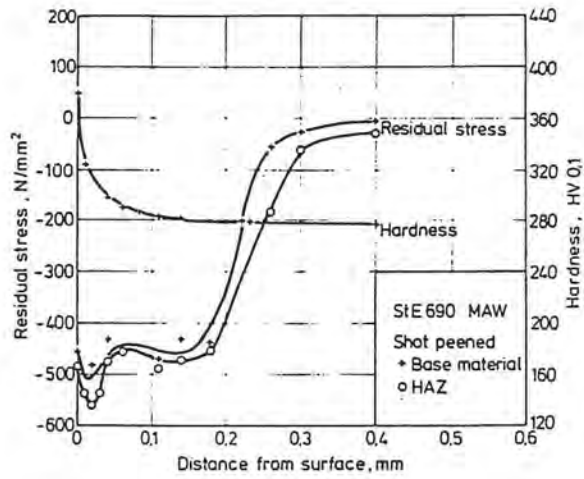


Fig 5 Distribution of residual stresses and of hardness after shot peening (steel StE 690, manual arc welded)

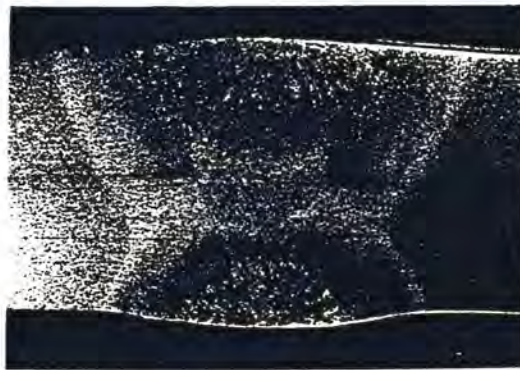


Fig 6 Weld profile after TIG welding

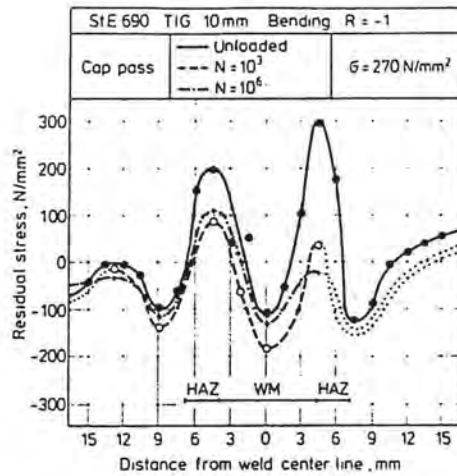


Fig 7 Distribution of welding residual stresses and their change after fatigue loading ( $N$  = number of load cycles)