# INVESTIGATIONS ON DUCTILITY AND FRACTURE OF COMPOUND STEEL WELDMENTS

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Brittle zones may be formed near the fusion line of compound steel weldments due to mixing of different materials and diffusion of carbon. To study their effect on the toughness of welded joints a new testing procedure was developed which allows to simulate service conditions and to locate the fracture exactly in the weakest microstructural area. Weldments joining carbon and high chromium steels were investigated in the as welded condition and after stress relieve. The latter at least promotes the formation of neighbouring thin brittle and soft layers and lowers the NDT.

## THE FORMATION OF BRITTLE LAYERS IN HETEROGENEOUS WELDED JOINTS

In general the mechanical properties including impact strength have to meet the same specifications in both the base metal, the heat affected zone (HAZ), and the weld metal. Lower impact values in the HAZ are rather rarely accepted. On the other hand the structural transformation in the HAZ of the weldments of hardenable carbon and alloy steels results in low toughness. This embrittlement is augmented with increasing carbon equivalent. A similar harmful effect may occur due to precipitation in all areas of the welding seam of microalloyed or alloy steels and can be expected especially after post weld heat treatment.

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Local embrittlement may also be experienced in the welding seams of steels having different chemical compositions and consequently different carbon activities. In such a weldment carbon as the element having a high diffusion coefficient tends to reach an equilibrium which is characterized by a constant carbon activity, i.e.

$$a_C = f_C \cdot [\%C] = \text{const} \qquad (1)$$

wherein [%C] is the carbon content in weight per cent and $f_C$ is the activity coefficient of carbon (1,2). Since the latter at given conditions depends on the chemical composition it is obvious that locally differing contents of elements which influence the activity coefficient of carbon necessarily lead to locally different carbon contents. One such element is chromium which as a carbide former reduces $f_C$. It follows that in the welding seam of two base metals having different chromium contents the carbon will diffuse in the direction to approach the thermodynamic equilibrium, i.e. the zones with higher chromium content. It follows further that the carbon content in the welding seam may vary widely due to the chromium distribution even if the two base metals have the same carbon content. Under appropriate conditions it is even possible that an uphill diffusion takes place, i.e. an increase of the carbon content in the chromium rich zones which initially had higher carbon contents than the adjacent material lower in chromium. Thus, carbon rich layers may develop in the HAZ depending mainly on the composition of the base metals but also on the filler metal, the time-temperature cycle resulting from the welding conditions and the post weld heat treatment. It is easy to understand that very hard and brittle layers may be formed in the HAZ of a high chromium steel especially if the second base metal is a carbon or a low alloy steel.

Indeed, thin brittle diffusion zones were observed in the weldments of steels having greatly different chromium contents. The two base metals were the martensitic stainless steel X5 CrNi 13 4 (Werkst.-Nr. 1.4313, max 0,07% C, max 1,0% Si, max 1,5% Mn, 12,0/13,5% Cr, max 0,70% Mo, 3,5/5,0% Ni) and the unalloyed fine grained steel TTStE 36 (Werkst.-Nr. 1.0859, max 0,18% C, 0,10/0,50% Si, 0,90/1,60% Mn and additions of Al or Nb or V) having high impact strength at low temperature. Three different filler metals, two high alloyed materials containing 13% Cr and 6% Ni or 23% Cr and 12% Ni respectively and an unalloyed welding consumable electrode were used. The said brittle layers had a

hardness of about 500 HV. This is much more than the unacceptable high hardness of 350 HV which is locally reached in the HAZ of carbon and low alloy steel weldments due to the formation of martensite and bainite.
Other experimental results from electron beam (EB) and manual metal arc (MMA) welding have shown that under certain conditions a narrow carbon depleted zone is formed adjacent to the brittle layer (3).

## PROCEDURE FOR THE EVALUATION OF THE TOUGHNESS OF HETEROGENEOUS WELDED JOINTS.

The aforesaid steels are widely used for components in hydraulic machinery and both steels offer sufficient toughness as base materials for this purpose. Otherwise, as explained earlier, their heterogeneous welded joint exhibits greatly differing chemical composition due to dilution and diffusion in the weld metal and the HAZ. This and the processes influenced by the thermal cycles such as transformation and precipitation result in locally varying microstructures and mechanical properties, first of all toughness. In fact, the measured Charpy-V impact values are greatly depending on the position of the notch root and can vary in a wide scatterband. For a disadvantageous position of the notch root it may even happen that the specified values are not being met not only at lower temperatures but also at 0°C, contradictory to the satisfactory and favourable results experienced in service. This explains why Charpy-V-tests are not necessarily appropriate to evaluate the safety of a heterogeneous welding seam against nonductile failure.
For that purpose an attempt was made to develop a more useful testing method for which the following considerations had to be taken into account (Fig 1) (4). The Pellini drop weight test like other limiting condition tests generates a running brittle crack and the arrest behaviour of that depends on the microstructural properties of the material in front of the crack. Other factors determine which microstructural layer will be hit by the running crack and because of the widely varying microstructural properties the scatter band of the results of the usual drop weight test can be very broad. Precracked Charpy type or other specimen precracked by fatigue suffer from the same disadvantage. Thus, in order to minimize the scatter it appeared desirable to place the fatigue precrack precisely in the weld seam layer of interest, i.e. the layer having the lowest resistance against crack propagation. The advantage of this procedure was already shown for

unalloyed weld metal (5 - 8). However, metallographic investigations of the weldments revealed that there is very little chance to exactly meet the envisaged microstructural layer because of its very small thickness which under certain conditions may be as low as .01 mm. On the other hand it is by no means certain that the low toughness of such a thin layer determines the overall fracture behaviour of the whole joint.

In order to receive reliable data for the evaluation of the resistance of a heterogeneous welding seam against non-ductile fracture the testing procedure to be developed including the specimen and the testing conditions were to adapt closely to the component and the loading conditions in service. Further, this procedure - contradictory to the Pellini-test where the running brittle crack may proceed in an arbitrary not exactly defined zone of the crack starter weld - has to guarantee that the fracture starts and developes in the layer having the weakest microstructure. The joint, of course, has to be representative for the critical zone of the work piece the safety of which against non-ductile fracture is to be assessed.

Summary the adapted test piece has to meet the same specifications regarding chemical composition, microstructure, geometry of weld preparation, surface geometry and roughness and has to be tested under the same or more severe conditions, i.e. temperature and loading rate as the work piece envisaged.

All these requirements can be met if a notched tension test specimen as shown in Fig. 2 is being used (9). In defining the geometry of the specimen it was considered that the most harmful configuration in a heterogeneous welding joint as the one under discussion is represented by a flat defect in the thin carbon depleted and weak zone adjacent to the fusion line of the weld seam. The notch in this plane of the specimen directs the highest tension to the critical zone. For the given two base metals, i.e. X5 CrNi 13 4 and TTStE 36 this critical weak zone is very thin and located in the HAZ directly adjacent to the fusion line (9). Thus a rounded notch with only 1 mm width is sufficient. As an important feature this notch allows the crack to initiate in the layer having the weakest microstructure which for its part acts as a metallurgical notch.

As no embrittling effect of thin layers in the HAZ have to be taken into account if loading acts in the longitudinal direction the course of the weld seam is transverse to the direction of the load in testing.

The most dangerous hardly detectable defects are located close to the surface of a component and have a depth of about the same size as the largest of those

defects which can not be detected by nondestructive (UT) testing. In stainless steel this limit corresponds generally to the reflection of a 3 mm diameter reference flat end hole. The actual defect size of such an indication in a work piece is about up to twice as big. Assuming a safety factor of 2 such a semicircular suface defect has a depth of 5 to 6 mm. For these reasons a 5,3 mm deep artificial notch in the specimen, as shown in Fig. 2 appeared appropriate.
As will be shown later improved information is obtained by testing this type of specimen. However, quantitative results concerning the effect of planar defects and imperfections as they may occur in weld joints are still rather restricted. For this kind of data a detailed fracture mechanics assessment of all relevant areas of the HAZ is required.

## EXPERIMENTAL METHOD AND MATERIAL

Both, notched tension tests and modified Pellini drop weight tests were carried out (9) by using specimens with identical notches (Figs. 2 and 3). The notch in the Pellini-type specimen replaced the usual brittle crack starter weld seam.
Most of the specimens were tested at 0°C which is a critical temperature since hydraulic machinery is not under service load below it. However, for the purpose of comparison with the results for the base metals other testing temperatures were also used. For the modified Pellini test they were in the range from +80 to -100°C and the notched tension tests were accomplished between room temperature and -100°C at a loading rate of 10N/mm$^2$s. Again for the purpose of comparision unnotched specimens taken from the same weld were tested too. The experimental arrangement for the tension tests is shown in Fig. 4.
The strain measurement on the surface of the sample appeared sufficient since the study aimed at the comparison of the toughness and rupture properties of weldments with different base and filler metals and not at the determination of absolute data for the ductility. Furthermore the investigations disclosed that the strain data measured by this rather simple method are at least to same extent representative also for the root of the notch as the amount of deformation in this area is almost equal to that on the surface.

TABLE 1 - Combination of Base and Filler Metals for the investigated Weldments.

| Plate No. | Base metal | Filler metal | Note |
|---|---|---|---|
| 8 | TT St E 36 | "CN 13/6-IG" | 1) |
| 9 | TT St E 36 | "FOX CN 23/12-A" | 2) |
| 10 | X5 CrNi 13 4 | "FOX EV 47" | 3) |
| 11 | TT St E 36 | "FOX CN 23/12-A" | 2) |
| 12 | X5 CrNi 13 4 | "FOX EV 47" | 3) |

1) Bright drawn copper coated wire (13% Cr, 6% Ni)
2) Titania mixed type electrode (23% Cr, 12% Ni)
3) Lime coated electrode (unalloyed)

The combination of base and filler metals for the investigated weldments are shown in Table 1. The weldments of plates 10 and 11 were investigated in the as welded condition, while plates 8, 9 and 12 after welding received a stress relieve heat treatment consisting of heating with 30°C/h to 580°C, holding at this temperature for 8 hours and cooling to roomtemperature with 30°C/h.

## RESULTS

Contradictory to the predominating opinion the notched tension tests revealed the possibility of a non-ductile fracture within the weldment (Fig. 5 and 6) and that this possibility exists even at low loading rates and not very low temperatures (0°C). It was established that under the given conditions such non-ductile fractures appeared only at the combined efforts of both, a notch as an artificial flaw and a thin brittle layer. This conclusion originates in the fact that the rupture of unnotched specimens always occured in the base metal and that for notched specimens a non-ductile rupture was only observed after a stress relieve heat treatment which at least promotes the formation of brittle layers. The tensile strength, on the other hand, was not influenced by the heat treatment.
The results of the notched tension tests indicate that nonductile failure of heterogeneous welding seams is possible due to the thin weak layers. Consequently these welds had to be tested under the extreme conditions of limiting condition tests (like the Pellini drop weight test) in order to prove the safety of components against brittle fracture at lowest possible temperatures and highest loading rates. For that purpose the newly developed modified Pellini test was used. Figure 7 shows

the summary test results of all tested filler metal welds at testing temperatures from +80°C to -100°C. Both, weldments with and without post weld heat treatment (PWHT) were investigated for all tests. The notch was located in the fusion line of the base metal of interest.
The comparison of specimens (with the same filler metal) in the as welded condition and after PWHT demonstrates that stress relief treatment results in deterioriating HAZ-toughness. The NDT-temperature for stress relieved weldments made with the austenitic 23% Cr-12% Ni filler metal was as high as -20°C. From Fig. 8 reproducing the cross section of such a modified Pellini specimen the artificial notch and the crack emerging from this notch and propagating along the fusion line can be seen. This macrophotograph also demonstrates that the crack was arrested at the boarder line to the austenitic weld metal. The latter is responsible for the blunting of the crack, too. Specimens broken at the somewhat lower temperature of -30°C showed a completely brittle fracture along the very weak layer in the HAZ close to the fusion line. This is clearly illustrated by Fig. 9 which shows the appearance of this fracture surface. Weldments of the same type in the as welded condition revealed a much better toughness, i.e. a lower NDT-temperature. Even at a temperature as low as -80°C no crack at the tip of the notch could be observed and at -100°C the non-ductile fracture took place outside the HAZ of the unalloyed base metal despite its initiation at the same place as for the specimens already described, i.e. the root of the artificial notch (Fig. 10)
For unalloyed filler metal the difference between the measured NDT-temperatures of specimens in the stress relieved and the as welded condition proved to be even greater, namely 100°C resulting from -30°C for FOX EV 47 as welded and +70°C for FOX EV 47 with PWHT.
Only post weld heat treated specimens were tested from the weldments using 13% Cr-6% Ni filler metal, since the difference of the chemical compositions between base and filler metal is almost the same as in the case of the unalloyed welding. Thus, no essentially different findings could be expected from specimens without PWHT.
Of course, the question arises if the NDT-tempertures determined with the modified Pellini specimens are comparable with material containing a flat sharp cracklike defect, loaded in a similar way. Various authors like Ingham and Watkins (10) and Düren (11) found transition temperature shifts of only 15°C as a maximum between notched and fatigue precracked brittle fracture test specimens. In the given situation the thin weak layer acts as a metallurgical notch and it should

be expected that the difference in the ductile-brittle transition would be even smaller than 15°C.
The hardening effect of the stress relieve heat treatment in the 5 to 20 μm thick diffusion zone near the fusion line, is well visible in Fig. 11 for the interface of the carbon steel TTStE 36 and the austenitic 23% Cr 12% Ni weld metal. A similar effect exhibit the bonds between the same unalloyed base metal and 13% Cr-6% Ni filler metal as well as the base metal X5 CrNi 13 4 and the unalloyed filler metal FOX EV 47.

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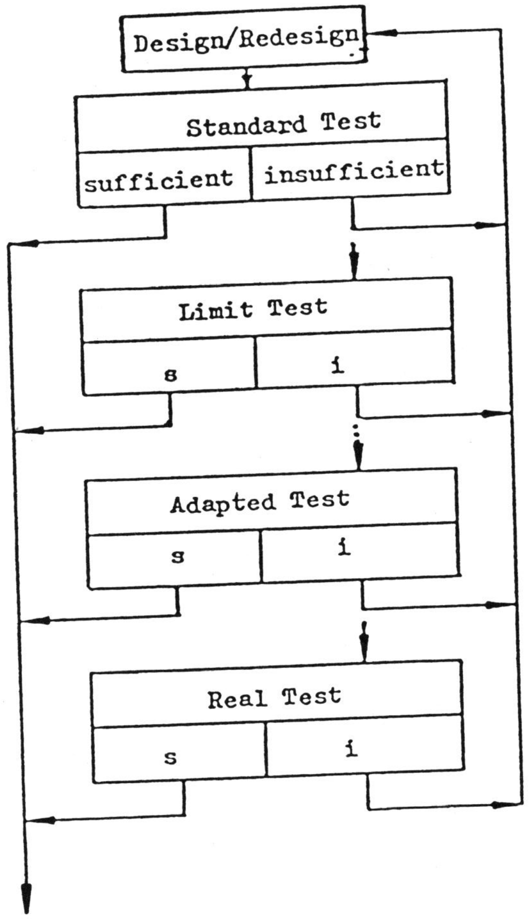
General sequence

Fig. 1: Sequence of testing steps: Standard test like Charpy-V-testing for toughness evalution are least expensive and give the most general but unspecific information. Limit tests apply to extreme conditions, which favor embrittlement, thus providing conservative judgement. Adapted tests simulate the actual loading conditions of the workpiece itself. The best and most specific results are given by real test conditions applied to the actual workpiece.

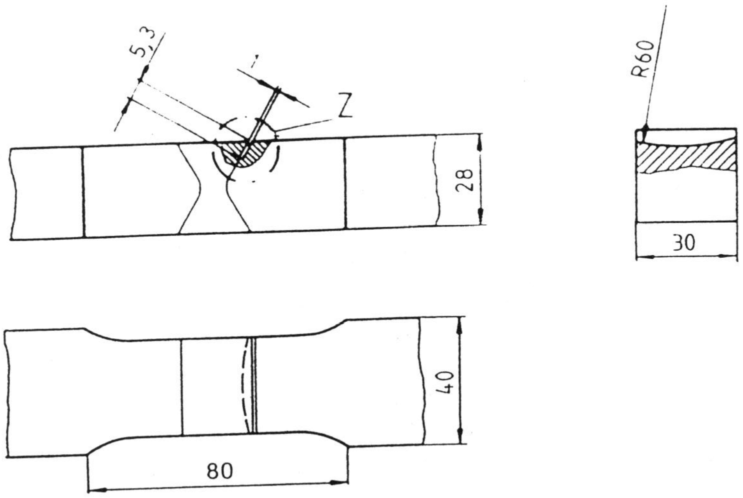

Figure 2: Notched tensile specimen

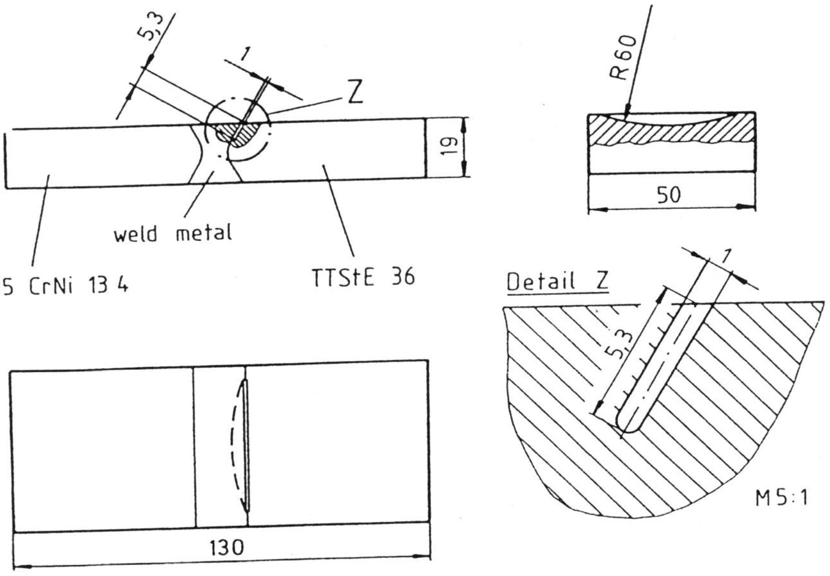

Figure 3: Modified "Pellini"-specimen

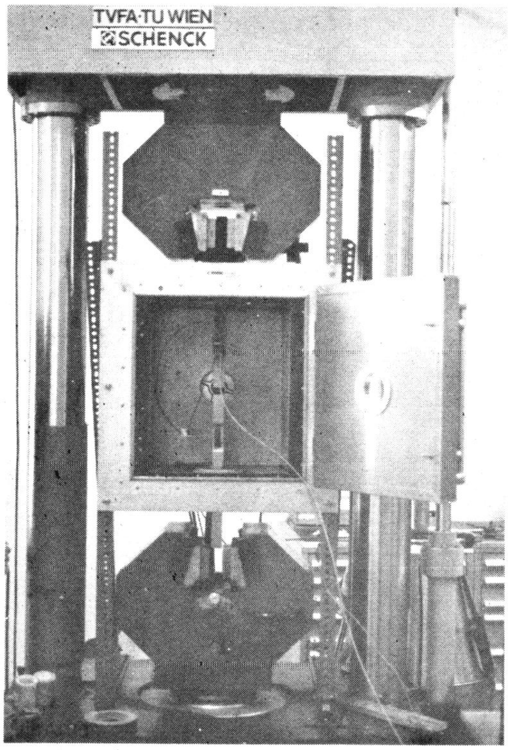

Fig. 4: Experimental arrangement for the tension tests.

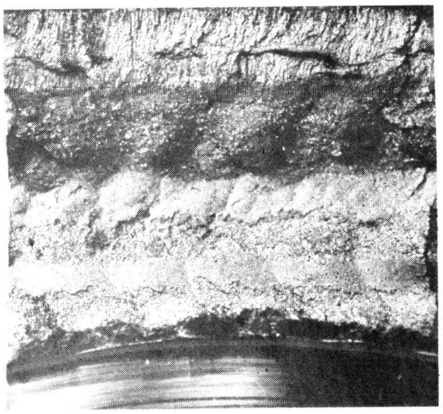

Fig. 5: Surface of the fracture along the weakest layer within the HAZ of a notched tensile specimen.
Filler metal: CN 13/6 IG. PWHT.
Testing temperature: 0°C
Loading rate: 10 N/mm s

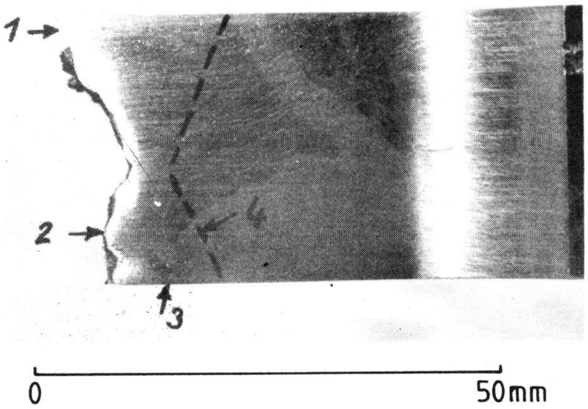

Fig. 6: Contour of the fracture of the notched tensile specimen as shown in Fig. 5.
1: notch
2: fracture area
3: welding seam
4: fusion line

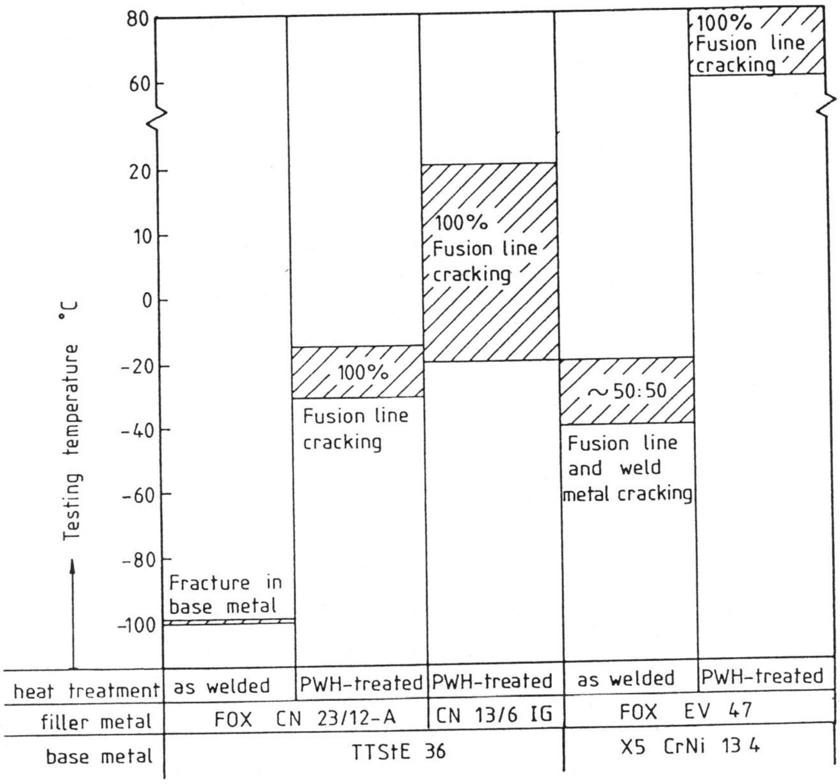

Figure 7: Test results using modified "Pellini"-specimens.

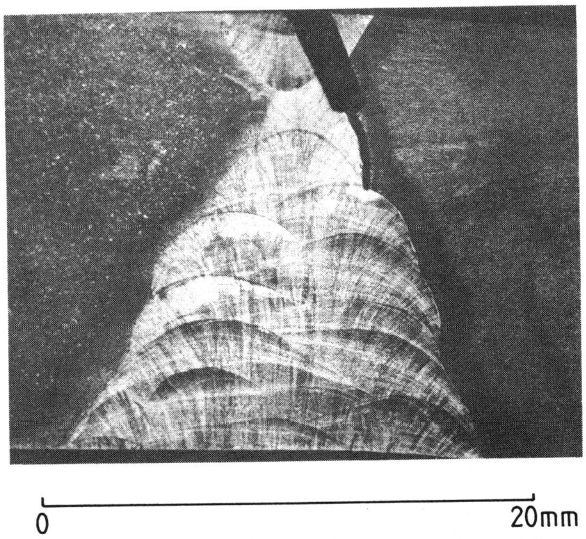

Fig. 8: Cross section of modified "Pellini"-specimen.
Filler metal: FOX CN 23/12-A. PWHT.
Testing temperature: -20°C

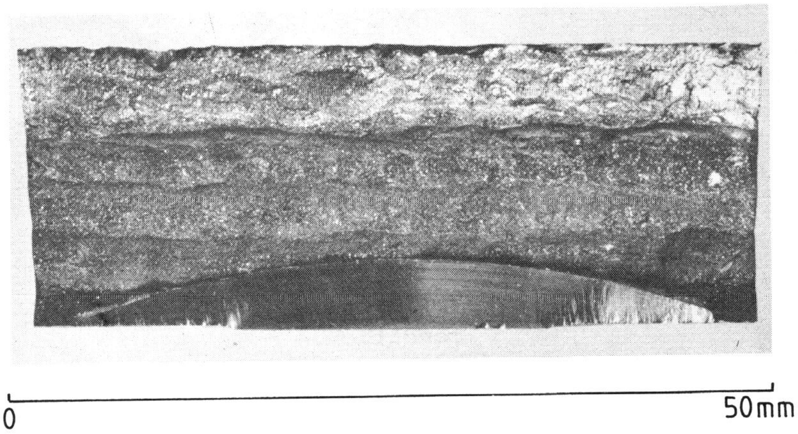

Fig. 9: Fracture area along the weakest layer of the HAZ, modified "Pellini"-specimen.
Filler metal: FOX CN 23/12-A. PWHT.
Testing temperature: -30°C

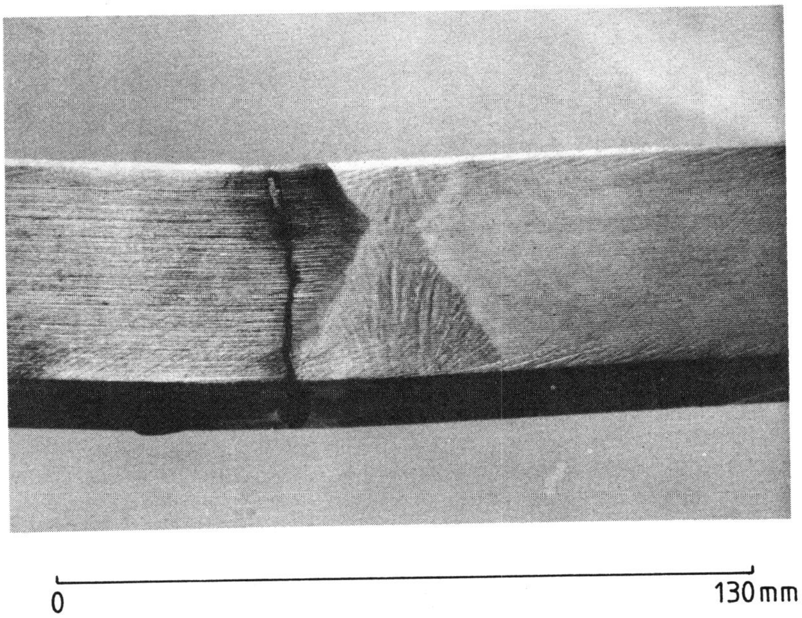

Fig. 10: Crack intiated in the notch and propagated in base metal TTStE 36, modified "Pellini"-specimen.
Filler metal: FOX CN 23/12-A. As welded condition.
Testing temperature: -100°C

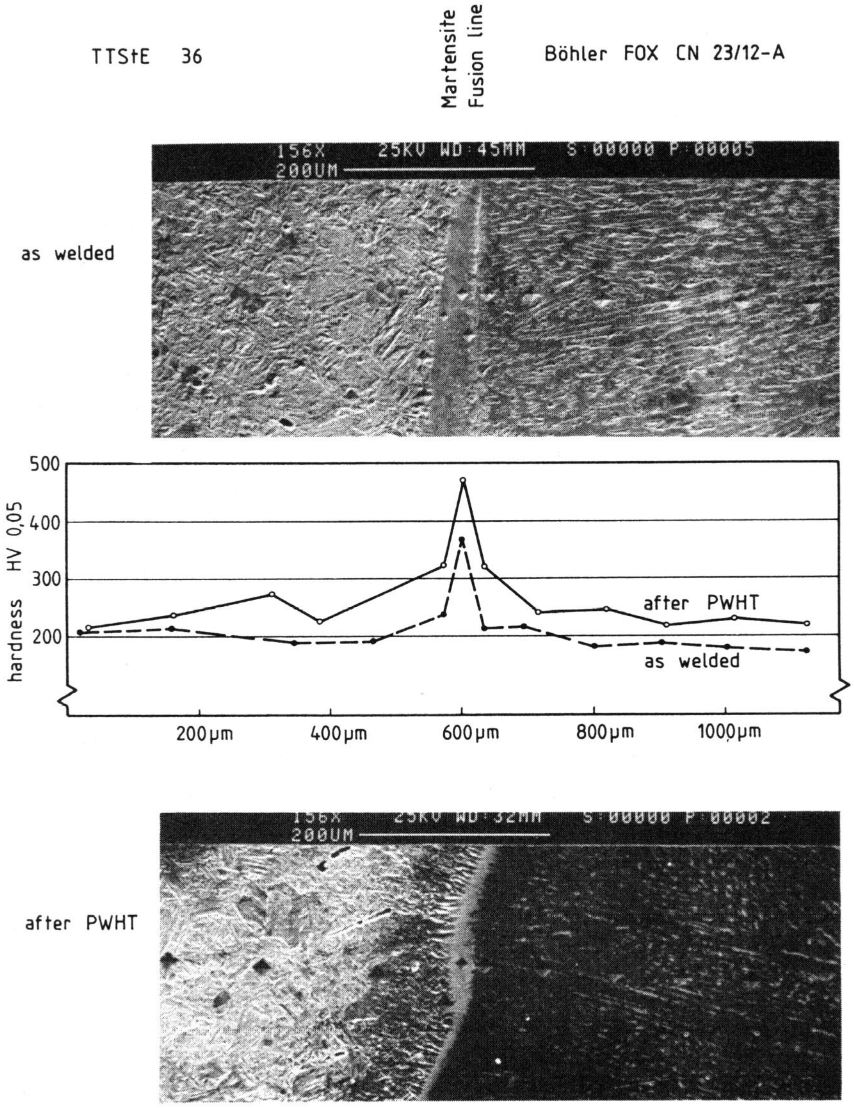

Fig. 11: Microstructure and microhardness of the austenitic weld metal, the HAZ, and the base metal TTStE 36, as welded and after PWHT.