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TENSILE PROPERTIES OF IRRADIATED AND FATIGUE EXPOSED STAINLESS STEEL DIN X 6 CrNi 1811 (SIMILAR TO AISI TYPE 304) PLATE AND WELDED JOINTS

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ABSTRACT

Test specimens of plate metal and welded joints of stainless steel DIN 1.4948, which is similar to AISI type 304, have been irradiated at 723 K and 823 K up to fluences of $1.10^{23}n.m^{-2}$ and $5.10^{24}n.m^{-2}$ (E > 0.1 MeV). These are representative conditions for the SNR-300 reactor vessel and inner components after 16 years of operation. High-rate ($\dot{\varepsilon} = 1\ s^{-1}$) tensile tests were performed after fatigue exposure up to various fractions of fatigue life (D) ranging from 5% to 95% at the same temperatures as the nominal temperatures of the irradiation series. Fatigue tests were performed in air under total axial strain control with a strain range of 0.6% at constant strain rate of $3.10^{-3}s^{-1}$.

Prior fatigue exposure (D-values ranging from 0.05 to 0.5) caused an increase of the tensile flow stresses and a decrease of tensile ductility values. These two effects balanced in such a way that the toughness was not significantly affected. However, from additional experiments, a decrease of the toughness was observed after fatigue exposure at the higher strain ranges of 1.0% and 2.0%.

Fatigue cracks started to affect the measured tensile properties for D-values between 0.5 and 0.7. After fatigue exposure to more than 70% of fatigue life (D > 0.7), tensile properties rapidly deteriorated. The fatigue cracks were so large in comparison with the specimen diameter that the geometry of the defected specimens strongly determined the measured values.

Irradiation did not significantly affect the tensile properties after fatigue exposure. However, irradiation can cause the appearence of large

fatigue cracks after a smaller number of cycles than in the case of unirradiated material, thus affecting the N-value at which the tensile properties deteriorate. Weld defects have a similar effect.

KEYWORDS

TENSILE PROPERTIES
PHYSICAL RADIATION EFFECTS
FATIGUE
STEEL-DIN-1-4948
PLATES
WELDED JOINTS
MECHANICAL TESTS
STRAINS
FLOW STRESS
FRACTURE PROPERTIES
CRACKS
EXPERIMENTAL DATA
GRAPHS
TABLES
HIGH TEMPERATURE
DAMAGING NEUTRON FLUENCE
MECHANICAL FRAGMENTATION
EVALUATED DATA

CONTENTS

INTRODUCTION

For the safety analyses of the liquid metal fast breeder reactor SNR-300, experimental data are required on the influence of neutron irradiation on the mechanical properties of the construction steel DIN 1.4948, which is similar to AISI type 304. Tensile properties at high strain rate ($\dot{\varepsilon}$ 1 to 10 s^{-1}) have to be used in the analysis of the hypthetical core disruptive Bethe-Tait accident. Components of the reactor are, in addition to neutron irradiation, exposed to cyclic strains from changing temperatures during reactor operation [1]. Therefore, it is highly relevant to look for the combined effect of neutron irradiation and low cycle fatigue on the high strain rate tensile properties, and more specifically on the toughness of the material, since the capacity to absorb energy strongly determines the capability to maintain structural integrity.

This report deals with tensile properties after prior fatigue loading of plate metal and welded joints of DIN 1.4948 at the strain rate of 1 s^{-1} at 723 K and 823 K. Irradiations were performed in the High Flux Reactor at Petten at 723 K and 823 K. The achieved fast fluence levels were $1.10^{23} n.m^{-2}$ and $5.10^{24} n.m^{-2}$ (E > 0.1 MeV), the respective thermal fluences were $6.10^{22} n.m^{-2}$ and $2.10^{24} n.m^{-2}$. The fast fluences are representative for the reactor vessel and shield tank respectively after 16 years of reactor operation. The thermal fluences are expected to be achieved after much shorter times, i.e. 1.5 and 6.5 years for the reactor vessel and shield tank respectively.

Total axial strain-controlled fatigue testing was performed at a strain range $\Delta\varepsilon_t$ of 0.6% and a strain rate of $3.10^{-3} s^{-1}$. The strain range is rather high with respect to the thermal strains that are expected to occur in the reactor components. The strain rate is several orders of magnitude higher than the actual cyclic strain rates. It is well known from the literature that the effect of the overcharge of these parameters is opposite: lower strain ranges give higher N_f-values but lower strain rates give lower N_f-values [2].

Fatigue exposure prior to tensile testing was performed at 723 K and 823 K after irradiation at the same temperatures. The different percentages of the total fatigue life ranges from 0.05 to 0.95 fatigue fraction ($D = N/N_f$).

EXPERIMENTAL CONDITIONS

The material DIN X 6 CrNi 1811 (Werkstoffnr. 1.4948), similar to AISI type 304, was produced by Stahlwerke Südwestfalen AG according to specifications of the heats of the actual reactor vessel of the SNR-300. The number of the heat is 231861. After rolling, the 20 mm thick plates have been solution annealed and quenched. The microstructure of the steel is recrystallized fully austenitic with grain sizes varying from ASTM-No 3 to 5. The chemical composition is given in Table 1.

The welded joints were made by welding the plates from this heat. The form of the welded joint is shown in figure 1, together with the welding conditions. The chemical composition of the filler wire and electrodes are given in Table 2. The ferrite percentage, metallographically determined, ranged from 3 to 6%. Weld quality was controlled by means of X-ray testing of the full plates. The inspection and acceptance was following DIN 54.111.

The specimens were made from 20 x 20 x 100 mm blocks, taken perpendicular to the rolling direction of the plates. Dimensions of the specimen are shown in figure 2. The gauge-length has a slight hour-glass shape to provide fatigue cracking in the middle of the specimen.

The blocks for the welded specimens were taken perpendicular to the weld axis. These blocks were X-rayed in four directions in order to search for any weld defects which had not been observed by the prior inspection of the original welded plates. The location of the specimen with respect to the weld beads is shown in figure 3. More details about specimen production and manufacturing inspection are given in the Appendix 1 of the report ECN-67 [3].

The irradiations were performed in the High Flux Reactor (HFR) at Petten, The Netherlands, with NAST- and TRIO-rigs [4]. The fluences were $1.10^{23} n.m^{-2}$ ($E > 0.1$ MeV) and $6.10^{22} n.m^{-2}$ thermal after 86.4 ks irradiation time and $5.10^{24} n.m^{-2}$ ($E > 0.1$ MeV) and $2.10^{24} n.m^{-2}$ thermal after 1.6 Ms irradiation time. The specimens were submerged in liquid sodium with an oxygen content less than 10 ppm. The specimen temperatures were kept within the margins of ± 20 K from the nominal irradiation temperatures for more than 95% of the irradiation time. Irradiations at 823 K were performed up to both fluence levels and at 723 K up to the high fluence level only.

The reference specimens were heat treated in air, during the same times and at the same temperature as the specimens used in the irradiations. The resulting 12 material conditions are listed in Table 3.

Mechanical testing was performed in air on an INSTRON servo-hydraulic machine. Axial strain controlled low cycle fatigue tests were performed at a constant strain rate of $3.10^{-3}s^{-1}$. Tensile tests after low cycle fatigue were performed after interruption of the fatigue exposure in the tensile part of the cycle and unloading of the specimen to the zero load zero strain condition. More details about the mechanical testing are given in the reports on low cycle fatigue (ECN-44, 67) [5,2] and tensile tests (ECN-32, 43) [6,7]. The testing was done in 12 series of ten specimens of one of the material conditions from table 3. The specimens were fatigue exposed up to various fractions of fatigue life ranging from 5% to 95%.

EXPERIMENTAL RESULTS

Mechanical testing

All the measured data from the high-rate tensile tests on irradiated and reference specimens are listed in the tables 4 to 9. This concerns the yield stresses at off-set values ranging from 0.2%- to 10% (discrete values of plastic strain), the UTS values and the ductility values. Included in these tables are the numbers of prior fatigue cycles and the corresponding D-values. For fatigue fractions up to 70% the percentage of fatigue life (D-value) was based on the mean number of cycles to failure ($\overline{N}_f$). Because of the scatter of the N_f-values, the higher fractions had to be estimated from the decrease of the actual stress amplitude compared to experiments which were run to failure. Each of the six tables gives the results from one test series on irradiated specimens together with the corresponding reference specimens. The results from the tables will be discussed in more detail hereafter.

A comparison of the full tensile curves of plate metal and welded joints withour prior fatigue exposure and after 1000 prior fatigue cycles is given in figure 4 and 5 respectively. The three irradiations and the corresponding ageing treatments of the unirradiated specimens are indicated with the letters A, B, and C following the designation from table 3. The indicated test temperatures are the same as the irradiation temperatures. In general, there is no significant irradiation effect, but for the plate metal without prior fatigue loading an irradiation hardening effect of about 20 MPa after irradiation at 823 K to $5.10^{24}n.m^{-2}$ (E > 0.1 MeV) can be observed. Further it can be seen that there is a strong difference between plate metal and welded joints, the latter showing higher yield stresses and lower ductilities. The largest effect on the tensile properties is due to prior fatigue exposure. In the following sections we will look at the experimental results more closely with respect to this effect.

Plate metal

High-rate tensile flow stress values are plotted in figure 6 as a function of D for unirradiated plate metal tested at 823 K. With respect to the effect of prior fatigue exposure, three areas can be seen in this figure:

- area I, D between 0 and 0.05,
  the region where the tensile flow stress values increase rapidly with increasing D-value;
- area II, D between 0.05 and 0.6,
  the region where the tensile flow stress values are nearly constant;
- area III, D between 0.6 and 1.0,
  here the tensile flow stresses rapidly decrease with increasing D-value. For the UTS the decrease starts at lower D-values than for the tensile yield-stresses.

All measured 0.2-yield stress values and the UTS values are plotted in a similar way in figure 7. The same behaviour as shown in figure 6 can be observed for all material conditions. No distinction between irradiated and unirradiated test results can be made. All data fall within scatterbands of about 40 MPa. This includes the data for 723 K and 823 K.

The figures 7, 8 and 9 give plots for the ductility data versus D. Similar areas as shown in the foregoing figures can be seen. Region I shows a decrease of tensile ductility, for D between 0.05 and 0.6 the ductility values remain constant and in region III rapid decrease of ductility-values with increasing D-values can be observed. No difference between the data for the six material conditions can be found. Up till D-values of about 0.5, the width of the scatterband is determined by the variety of the ductility properties without prior fatigue. At higher D-values, the scatterband for total and uniform elongation is even smaller, showing the merit of the more accurate procedure for estimating D-values by following the decrease of the stress amplitude. This does not appear in figure 10 on reduction of area (RA), due to difficulties with RA-measurements on fatigue-cracked specimens.

In report ECN-67 the cyclic hardening behaviour of plate metal DIN 1.4948 at 723 K and 823 K has been extensively described [3]. In that report it is shown that the cyclic hardening strongly depends on the applied strain range; cycling at the high strain range of 2.0% hardens the material to even higher stress values than the UTS value of the original material. The measured tensile flow stress values reflect the amount of cyclic hardening achieved during the prior fatigue loading. The 0.2-yield stress values are even almost equal to the cyclic stress values during the last fatigue cycles. Figure 11 shows that the high-rate tensile curves are considerably affected by prior fatigue at higher strain ranges. Here curves for plate metal DIN 1.4948 at 823 K are shown after prior fatigue exposure up to 10% of fatigue life at different strain amplitudes. Note the very high yield stress value and the remaining relatively large deformation capacity after prior cycling at a strain range of 2.0%.

The effect on toughness, of prior fatigue loading at a strain range of 0.6%, is shown in figure 12. Normalized toughness, expressed as the ratio of the area under the load-displacement curves with and without prior fatigue loading, are given for plate metal DIN 1.4948 at 823 K. It is shown that for D between 0 and 0.05 the slight decrease of the ductility is balanced by the considerable increase of the yield stress. There is even a slight benificial effect of prior fatigue cycling, although this effect is negligible when seen in relation to the scatter of the toughness of the plate metal without prior fatigue exposure. For the range of D-values between 0.05 and 0.6, where tensile properties were constant, also a constant value of the toughness is shown. For the high D-values ($D > 0.6$) the decrease of tensile properties cause a decrease of the toughness too. Here the toughness values get below the scatterband of the original material. In the same figure, also the normalized uniform toughness values (area under the curve up till tensile instability at the uniform strain) are plotted. At low D-values ($D < 0.05$) a slight decrease is shown and the onset of the rapid decrease can now be observed at the lower D-value of 0.5. At the high D-values ($D > 0.8$) the two curves coïncide, showing that there is no necking after prior fatigue loading to such high fractions of fatigue life.

Fatigue exposure at the higher strain ranges of 1.0% and 2.0%, caused considerable decrease of toughness, although the yield stress increased to 3 times the original yield stress value or even to a value above the original UTS (fig. 11). This is shown in figure 13, giving trend lines for toughness after fatigue at these strain ranges.

Welded joints.

Tensile stresses at discrete values of constant plastic strain (off-set values) of welded joints at 823 K without and with prior fatigue cycles are shown in figure 14. Similar effects of prior fatigue exposure as observed on plate metal can be seen: increase of tensile flow stress

values at low D-values, constant values for D between 0.05 and 0.6 and rapid decrease for D > 0.6.
The 0.2-yield stress of welded joints is about twice as high as the value for plate metal. Tensile strain hardening is significantly less than that of plate metal.

In figure 15, giving results from ECN-67 [3], it is shown that welded joints show less cyclic hardening than plate metal. In accordance with this cyclic hardening behaviour of welded joints, the increase of the flow stress in the region 0 < D < 0.05 is smaller than for plate metal.

All measured 0.2-yield stresses and the UTS data for welded joints are plotted in figure 16. Contrary to the observations on plate metal, there is a significant difference between the data from specimens irradiated or aged at 723 K on the one hand and 823 K on the other hand and tested at the same temperatures. The 0.2-yield stress values at 723 K are about 50 MPa higher than the values at 823 K, the UTS values are about 80 MPa higher.

The figures 17, 18 and 19 on tensile ductility of welded joints after prior fatigue exposure, show similar behaviour as observed for plate metal. No significant difference between the different conditions and consequently also no difference between data at 723 K and 823 K can be observed. Ductility values of welded joints are lower than those of plate metal, the scatterband width of the reduction of area(RA)-values is about twice as high as that for plate metal due to the variability of RA-measurements on inhomogeneous specimens from welded joints.

In toughness values, welded joints after prior fatigue exposure at a strain range of 0.6% showed the same behaviour as plate metal: no significant change for D-values up to about 0.5 and a strong decrease of toughness at higher D-values.

Metallography

Transmission electron microscopy (TEM)

After the low fluence irradiations no change of the microstructure could be observed. Neither loop-type precipitation of displacement damage nor significant void formation was observed after the high fluence irradiations. Some minor effects, which could be observed after the high fluence irradiations, were (figure 20):

- a slight decoration of some existing dislocations after irradiation at 723 K as well as 823 K,
- small helium bubbles which were occasionally observed after irradiation at 823 K only.

A characteristic dislocation substructure was formed during fatigue testing. Figure 21 shows the microstructure as observed in the plates from which the specimens were produced. The low dislocation density, typical for 1% tensile deformation of a fully annealed austenitic stainless steel, is due to the techniques used in practice for the production of the steel plates (quenching, stretching). Figure 22 shows the regular but inhomogeneous distribution of dislocations, characteristic for the dislocation substructure after prior fatigue exposure. This typical cell-structure consists of areas of deformation free material surrounded by a dense network of dislocation clusters. The dislocation structure of a specimen which has been tensile tested after prior fatigue, is shown in figure 23. The deformation free areas, as observed after fatigue testing, are now heavily deformed as shown by the uniform dense dislocation distribution.

Optical microscopy

The only significant change in the microstructure, as observed by optical microscopy, was the presence of transgranular surface cracks after prior fatigue loading. Figure 24 shows these surface cracks in a broken plate metal specimen at a D-value of 70%. Note that the cracks are widely opened and blunted and that no significant crack extension due to the monotonic (tensile) loading can be observed.

We have shown earlier in the ref. [3] that fatigue micro-crack density and crack-length as observed in specimens which have been low cycle fatigue tested to failure, strongly depend on the applied strain range. Results from measurements on specimens from this work, with D-values of 0.50 and 0.75, are plotted together with those earlier results in figure 25. The increase of the fatigue macro-crack density and the crack-length with increasing D-values is clearly demonstrated. This effect is also shown in figure 26. Here the increasing damage of the circumferential surface of a series of specimens, arranged with increasing D-values, is shown. In addition the corresponding decrease of tensile elongation and the disappearance of necking can be observed.

In figure 27a and b two plate metal specimens with relatively high (a) and low (b) ductility values are compared. The latter, showing significant void formation due to inclusions, demonstrates the important role of inclusions on the ductility of plate metal.

Fracture of welded joints was located in the middle of the weld (figure 28). No effects of weld defects on the tensile fracture have been observed.

Fractography

Fractographic observations showed fully ductile (dimpled) fracture surfaces after prior fatigue up to about 50% of fatigue life. Examples of such fractures of plate metal and welded joints are shown in figure 29a and b. Note the fine dimples of the welded joint. On those specimens which were fatigue exposed up to D-values ranging from 0.5 to 0.95, a combination of fatigue fracture at the outer fringe and tensile fracture of the remaining part was observed. The fractions of the fracture surface occupied with fatigue fracture increased with increasing number of prior fatigue cycles N as shown in figure 30. No significant difference between irradiated and unirradiated steel can be observed. The slopes of the curves are steeper for welded joints than for plate metal.

Intergranular fracture, as shown in figure 31, was occasionally observed, but only on the fracture surfaces of the specimens irradiated at 823 K. However, this localised intergranular fracture of a few isolated grains did not affect the fatigue fracture nor the tensile fracture.

With respect to fatigue crack formation, effects of inclusions in plate metal and of weld defects in welded joints similar to those reported in reference 3, were also observed in this work.

With respect to tensile fracture, no effects of small weld defects were observed. Figure 32 gives an example of secondary cracking due to a stringer of inclusions in the tensile fracture area of a plate metal specimen.

DISCUSSION

Results of tensile testing, fatigue testing and metallographic observations on irradiated DIN 1.4948 have been reported in the open literature [1,3,5-11]. For the discussion of the pure fatigue tests we refer to the reports ECN-43 and ECN-67 respectively [6,3]. From these reports we will recapitulate those results which are relevant for the discussion of this work.

Pure tensile testing ($\dot{\varepsilon}$ = 1 s^{-1}) at 723 K and 823 K.

- The variability of the tensile properties of this heat of plate metal DIN 1.4948 (heat no. 231861) is 40 MPa for the 0.2-yield stress, 30 MPa for the UTS and 10 percentage points for the total elongation.
- Tensile yield stress values of welded joints are about twice as high as those of plate metal, total and uniform elongation are about half as high.
- High-rate tensile properties of plate metal at 723 K do not significantly differ with those at 823 K, UTS values of welded joints are about 70 MPa higher at 723 K than at 823 K.
- There is no significant effect of irradiation on high-rate tensile ductility.
- Tensile flow stresses increase with about 20 MPa after irradiation up to $5.10^{24}n.m^{-2}$ (E > 0.1 MeV) at 823 K.

Pure fatigue testing ($\dot{\varepsilon}$ = $3.10^{-3}s^{-1}$) at 723 K and 823 K.

- Cyclic hardening of welded joints is less than that of plate metal.
- Cyclic stresses of plate metal at 723 K and 823 K do not differ significantly.
- Cyclic saturation stress values of welded joints at 723 K are about 50 MPa higher than at 823 K.
- N_f-values of welded joints are about half those of plate metal.
- N_f-values at 723 K are higher than at 823 K.
- The small irradiation hardening effect after irradiation at 823 K to $5.10^{24}n.m^{-2}$ (E > 0.1 MeV) decreases with increasing number of fatigue cycles.
- There is no effect of irradiation on N_f at 723 K.
- The scatter of N_f increased with increasing neutron fluence after irradiation at 823 K.

- Reduced fatigue lives after irradiation were due to a change of the fatigue crack initiation mechanism from transgranular to intergranular.
- Stage II - type fatigue crack-growth (tensile-opening mode I crack growth or striated crack growth) was not influenced by irradiation.
- Material inhomogeneities like inclusions in plate metal and weld defects in welded-joints strongly contribute to the scatter of N_f, and they play an important role in enhancing fatigue crack initiation.

The present results of the combined fatigue-tensile tests can now be fully explained on base of these observations.

The tensile flow stresses are determined by the state of cyclic hardening achieved during the prior fatigue loading, as shown by the equivalence of the 0.2-yield stress values and the cyclic stress values in the last preceeding fatigue cycles. This hardening is accompanied by a decrease of ductility. Over the range of D-values between 0.05 and 0.5 the tensile properties remain constant as a consequence of stabilisation of the stress-strain hysteresis loops after about 5% of the fatigue life. The 0.2-yield stresses reflect this stabilisation of the cyclic stresses after about 5% of fatigue life.
In accordance with the lower cyclic hardening of welded joints DIN 1.4948, the increase of the 0.2-yield stress after fatigue exposure of welded joints is less than the increase for plate metal.
The observations that post-fatigue tensile properties of plate metal at 723 K and 823 K do not differ and that the UTS values of welded joints are about 80 MPa higher at 723 K than at 823 K, are in agreement with the pure tensile test results.
The one and only minor irradiation effect on the pure (high-rate!) tensile properties, i.e. an increase of the tensile flow stresses of about 20 MPa after irradiation at 823 K up to $5.10^{24} n.m^{-2}$, has disappeared due to the prior fatigue loading.

With respect to the capacity of the material to absorb energy, it appears from the toughness that the decrease of the ductility is balanced by the increase of the yield stress after prior fatigue exposure up to about 50% of fatigue life at a strain range of 0.6%. However fatigue loading at higher strain-amplitudes significantly reduces the toughness.

The effect of the increase of the yield-stress with about 300 MPa after prior fatigue at a strain range of 2.0% can be quantitatively described by the Hall-Petch formula:

$$\sigma_y = \sigma_o + K_y\, d^{-\frac{1}{2}} \qquad \text{-I-}$$

using for d the subgrain diameter of 0.4 µm and using Norström's value of 6 $N.mm^{-3/2}$ for K_y [12].
The relation in this form, does not give the right values for the increase of the yield-stress after fatigue at lower strain amplitudes when the diameter of the dislocation cells is also about 0.4 µm. This may be due to the fact that the cells formed after fatigue at lower strain ranges are less perfect and the dislocation density in the cell walls is lower. In that case the cells seem not to act as real subgrains.

The relatively large deformation capacity after cyclic hardening to a yield-stress value even higher than the UTS value of the original material, can be qualitatively explained from the metallographic observations. The formation of a dislocation cell structure, with dislocation free material within these cells, allows for additional plastic deformation in these cells by subsequent tensile testing.

The strong decrease of the tensile properties and toughness values after fatigue up to D-values higher than 0.5, is due to the significant damage from fatigue cracks. From the metallographic observations it is deduced that it takes about 50% of fatigue life to form a leading crack with 100 µm length (depth) under the applied fatigue conditions. Neither the tensile properties nor the toughness values for $D > 0.5$ are therefore representative material properties, they only reflect the increasing damage from fatigue cracks. In the case of $D > 0.5$ more than 1% (about 100 µm) of the thickness of this specimen is penetrated by fatigue cracks and one has to use a fracture mechanics approach to characterise the behaviour of this defected material.
Nevertheless, the tensile ductility values for $D > 0.5$ give a good picture of the fatigue crack-growth during the final stage of fatigue life. In this respect it is important to note that the earlier observations from ECN-67 Ref. [3] are confirmed by this work:

- stage II fatigue crack-growth is not influenced by irradiation,
- effects of irradiation or material inhomogeneities like inclusions in plate metal or weld defects in welded joints, causing increased scatter of the N_f-values, are mainly due to enhanced fatigue crack initiation,
- fatigue life is not affected by occasional local intergranular fracture due to irradiation at 823 K when only a few isolated grains fracture intergranularly.

CONCLUSIONS

Prior fatigue exposure up to no more than 50% of fatigue life ($D < 0.5$) causes an increase of the tensile flow stresses and a decrease of tensile ductility. The increase of the 0.2-yield stress is equal to the amount of cyclic hardening achieved during the prior fatigue.

Toughness is not significantly affected by prior fatigue at a strain range of 0.6% for D-values up to 0.5. At higher applied strain ranges the toughness decreases after prior fatigue exposure.

After prior fatigue loading up to more than 50% of fatigue life, ($D > 0.5$) significant damage from fatigue cracks causes a strong reduction of flow-stress, ductility and toughness values. Under these circumstances we are dealing with defected specimens and one would have to use a fracture mechanics approach to characterise the material behaviour.

Irradiation only affects the high-rate tensile properties after prior fatigue in this respect that it can reduce fatigue life and increase the scatter of the N_f-values by promoting stage I-fatigue crack formation due to intergranular cracking of a group of grains after irradiation at 823 K. The combination of irradiation and fatigue can thus cause a decrease of the tensile properties due to fatigue cracks after a smaller number of prior fatigue cycles than in the case of unirradiated material.

In the case of welded joints, considerable scatter of the N_f-values is caused by weld defects. They too can thus cause a decrease of the tensile properties due to fatigue cracks after a smaller number of prior fatigue cycles.

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	Classical technique	Trace element method	Certificate data heat 231861	Specification DIN 1.4948	Specification AISI 304
C	0.005	0.053	0.052	0.04/0.07	≤0.08
Cr	17.78	17.80	17.45	17.0/19.0	19.0/20.0
Ni	11.15	10.60	11.0	10.0/12.0	8.0/12.0
Si	0.44	0.39	0.44	≤0.75	≤1.0
Mn	1.82	2.25	1.81	≤2.0	≤2.0
P	0.023	0.014	0.019	≤0.03	
S		0.042	0.012	≤0.02	
N	0.041				
Mo		0.065		≤0.50	
V	0.04	0.04			
Nb	0.01	≤0.01			

Table 1. Chemical composition of the heat 231861 compared with specification data for DIN 1.4948 and AISI type 304. Weight %.

Element	Welded joints	
	TIG wire	4mm electrode FOK CN 1811
C	-	-
Cr	18.70	18.67
Ni	10.92	10.60
Mn	1.30	1.36
Si	.58	.63
Mo	<0.01	<0.01
B	-	-
P	.011	.017
S	-	-
Cu	<.01	.011
Co	<.01	0.07
N	-	-
Ti	<0.01	<0.01
Nb	<0.01	<0.01
V	<0.01	<0.01
Pb	-	-
W	<0.01	<0.01
Al	-	-

Table 2. Chemical composition of the filler wire and electrodes. Weight %.

	plate metal		welded joints	
	irradiated	reference	irradiated	reference
A	1.10^{23} n.m^{-2} (E > 0.1 MeV) at 823 K	aged for 86.4 ks at 823 K	1.10^{23} n.m^{-2} (E > 0.1 MeV) at 823 K	aged for 86.4 ks at 823 K
B	5.10^{24} n.m^{-2} (E > 0.1 MeV) at 823 K	aged for 1.6 Ms at 823 K	5.10^{24} n.m^{-2} (E > 0.1 MeV) at 823 K	aged for 1.6 Ms at 823 K
C	5.10^{24} n.m^{-2} (E > 0.1 MeV) at 723 K	aged for 1.6 Ms at 723 K	5.10^{24} n.m^{-2} (E > 0.1 MeV) at 723 K	aged for 1.6 Ms at 723 K

Table 3. Irradiation conditions of the irradiated specimens and ageing conditions of the unirradiated (reference) specimens.

PLATE AT 823 K.

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N_*	% N/N_f
117	140	158	188	261	380	47	35	67	-	-
115	140	168	190	267	376	47	36	69	-	-
227	250	265	294	345	397	41	28	66	1400	20
220	245	265	282	335	395	42	28	65	1400	20
224	245	265	282	340	385	41	28	64	3500	50
224	245	260	285	340	385	41	28	64	3500	50
228	250	270	285	345	390	33	22	40	4900	70
230	250	270	290	350	375	27	19	38	4900	70
230	250	270	290	338	357	25	17	27	5300	75
210	230	250	265	310	314	19	13	24	5625	80
Irradiated ($1.10^{23} n.m^{-2}$, E > 0.1 MeV).										
113	136	156	186	261	386	49	36	70	-	-
115	140	160	190	265	380	49	36	70	-	-
240	260	270	295	340	396	42	30	64	1400	20
240	250	265	296	340	398	42	30	66	1400	20
233	250	265	286	345	393	41	29	60	3500	50
235	250	265	285	338	403	42	30	60	3500	50
235	250	265	285	344	378	37	25	44	4900	70
240	255	270	290	340	380	36	22	42	4900	70
217	234	252	271	317	345	24	19	17	5700	80
215	232	245	270	330	337	20	15	16	6000	85
Heat treated in air during 24 hr.										

*$\Delta\varepsilon_t$ = 0.6% $\bar{N}_f$ = 7190.

Table 4. High-rate ($\dot{\varepsilon}$ = 1 s^{-1}) tensile properties after fatigue exposure of irradiated and unirradiated reference stainless steel DIN 1.4948 plate metal at 823 K.

PLATE AT 823 K.

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N_*	% N/N_f
132	148	173	211	288	367	39	28	64	-	-
238	247	261	280	343	380	36	23	61	500	5
230	247	263	288	354	386	35	20	62	2220	30
230	251	263	288	354	381	33	20	60	3700	50
230	247	263	280	349	378	32	20	57	4440	60
227	247	263	280	348	383	33	22	58	5180	70
226	251	263	288	340	370	26	19	44	5920	75
215	234	255	263	314	314	17	10	28	6660	85
156	271	174	-	-	176	8	2	17	6917	95
Irradiated (5.10^{24}n.m^{-2}, E > 0.1 MeV).										
118	144	165	187	271	352	38	30	67	-	-
226	238	255	271	335	368	36	24	65	500	5
227	241	255	280	342	378	34	24	66	4250	60
217	230	250	266	330	368	34	20	51	5100	70
222	232	250	270	329	357	24	18	43	5950	80
145	163	165	-	-	165	7	2	11	6750	95
218	230	247	267	314	321	16	14	31	6800	85
184	199	214	214	-	214	10	4	17	7417	90
Heat treated in air during 456 hr.										

* $\Delta\varepsilon_t = 0.6\%$, $\bar{N}_f = 7190$

Table 5. High-rate ($\dot{\varepsilon} = 1\ s^{-1}$) tensile properties after fatigue exposure of irradiated and unirradiated reference stainless steel DIN 1.4948 plate metal at 823 K.

PLATE AT 723 K.

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N_*	% N/N_f
148	164	181	218	288	387	43	35	64	-	-
140	158	176	214	273	386	43	35	66	-	-
214	228	247	265	320	393	40	28	62	500	5
225	239	255	280	349	403	40	28	61	1998	20
222	238	252	280	342	398	37	26	58	4995	50
222	242	252	280	348	398	28	21	38	6993	70
214	235	250	275	329	372	19	14	40	7992	80
148	170	181	190	-	190	8	4	9	8064	95
194	220	238	250	-	250	10	6	10	8991	90
Irradiated ($5.10^{24}n.m^{-2}$, E > 0.1 MeV).										
131	156	175	200	265	375	43	35	69	-	-
220	230	238	271	321	391	38	28	62	500	5
226	237	254	280	345	405	38	28	64	2050	20
218	230	250	275	345	408	38	28	60	5125	50
220	234	252	280	341	404	36	25	57	6150	60
219	232	255	280	344	391	30	20	42	7175	70
216	233	253	280	345	385	25	20	37	8200	80
178	197	210	229	-	230	8	4	13	9280	95
165	181	186	-	-	194	8	4	11	9375	95
Heat treated in air during 456 hr.										

$*\Delta\varepsilon_t = 0.6\%$, $\bar{N}_f = 10120$

Table 6. High-rate ($\dot{\varepsilon} = 1\ s^{-1}$) tensile properties after fatigue exposure of irradiated and unirradiated reference stainless steel DIN 1.4948 plate metal at 723 K.

WELDED JOINTS AT 823 K

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N *	% N/N_f
221	250	273	290	331	359	28	18	57	-	-
242	260	280	305	345	353	27	14	57	840	25
241	260	276	295	332	347	27	16	57	840	25
250	265	284	305	345	348	27	12	55	2100	60
231	242	263	294	326	336	24	14	50	2100	60
202	225	242	256	-	259	9	5	31	2794	90
216	237	255	268	-	276	12	5	29	2760	90
207	225	240	252	-	252	9	5	25	3374	95
215	235	248	272	-	278	15	8	33	3600	90
Irradiated ($1.10^{23}n.m^{-2}$, E > 0.1 MeV).										
228	250	272	302	342	349	30	15	55	-	-
214	241	259	285	333	349	29	18	53	-	-
259	266	281	294	342	352	28	15	56	990	30
243	269	282	294	337	347	28	16	52	990	30
250	261	280	307	341	350	26	12	53	2475	70
241	259	273	294	335	345	27	15	54	2475	70
240	256	270	294	310	314	17	10	42	3465	75
231	251	262	280	315	317	19	10	42	3465	75
218	233	245	254	285	290	15	9	17	4175	90
211	242	250	268	-	273	10	4	12	4455	95
Heat treated in air during 24 hr.										

* $\Delta\varepsilon_t = 0.6$, $\bar{N}_f = 3490$

Table 7. High-rate ($\dot{\varepsilon} = 1\ s^{-1}$) tensile properties after fatigue exposure of irradiated and unirradiated welded joints DIN 1.4948 at 823 K.

WELDED JOINTS AT 823 K.

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N_*	% N/N_f
230	263	280	304	350	350	23	11	55	-	-
265	281	296	312	342	342	22	10	60	250	5
255	280	294	312	334	334	22	10	60	700	20
255	280	290	312	334	333	21	10	53	1050	30
253	280	288	309	336	336	21	10	53	1290	35
226	255	268	280	-	281	9	6	25	1575	80
171	194	202	-	-	210	6	3	15	1990	90
125	138	141	-	-	141	5	3	10	2035	95
					Irradiated (5.10^{24}n.m^{-2}, E > 0.1 MeV)					
197	238	255	280	343	343	23	11	58	-	-
247	263	280	296	327	329	22	11	60	250	5
243	255	271	288	329	329	22	11	62	780	20
230	247	263	280	-	291	17	9	33	1500	75
230	247	260	260	-	260	10	5	27	1770	80
181	197	210	210	-	210	8	4	15	1875	95
183	203	222	222	-	224	10	4	20	1885	90
122	-	-	-	-	127	4	0.5	10	1920	95
					Heat treated in air during 456 hr.					

$*\Delta\varepsilon_t = 0.6\%$, $\bar{N}_f = 3490$.

Table 8. High-rate ($\varepsilon = 1\ s^{-1}$) tensile properties after fatigue exposure of irradiated and unirradiated welded joints DIN 1.4948 at 823 K.

WELDED JOINTS AT 723 K;

tensile properties									prior fatigue	
MPa $\sigma_{0.2}$	MPa σ_1	MPa σ_2	MPa σ_4	MPa σ_{10}	MPa UTS	% δ	% ε_u	% RA	cycles N_*	% N/N_f
250	271	289	312	378	408	28	20	51	-	-
250	271	288	312	378	414	28	20	50	-	-
304	325	337	359	395	411	26	16	46	250	5
284	315	329	350	403	420	26	18	48	1330	25
177	190	202	-	-	203	7	2	6	1330	95
288	312	329	350	395	401	23	.4	44	3325	60
245	263	280	298	-	298	12	5	23	3900	90
141	161	164	-	-	164	5	2	8	3940	95
259	291	308	321	-	324	14	5	11	4110	90
197	217	-	-	-	217	4	1	4	4130	95
280	312	321	345	381	381	17	10	22	4655	80
Irradiated ($5.10^{24} n.m^{-2}$. E > 0.1 MeV).										
235	262	281	312	370	395	31	18	61	-	-
280	304	321	343	380	393	30	14	59	250	5
270	288	308	330	378	390	31	14	60	1220	20
270	294	312	337	384	394	29	13	45	3050	50
268	292	312	337	390	395	26	13	40	3660	60
233	261	277	288	-	288	9	4	13	4230	90
230	263	280	288	-	288	10	4	16	4550	90
135	158	167	-	-	170	6	2	7	5100	95
245	285	311	328	-	348	17	8	25	5490	80
Heat treated in air during 456 hr.										

$^*\Delta\varepsilon_t = 0.6\%$, $\bar{N}_f = 5800$

Table 9.High-rate ($\dot{\varepsilon} = 1\ s^{-1}$) tensile properties after fatigue exposure of irradiated and unirradiated welded joints DIN 1.4948 at 723 K.

Fig. 1. Welded joint of DIN 1.4948.

Welding conditions:

root pass TI9 WELDING (ARGON)

2 mm filler wire CN 1811/IG

other layers ELECTRIC RESISTANCE HANDWELDING

4 mm FOK CN 1811 electrode

20/24V - 125/140A

no heat treatments

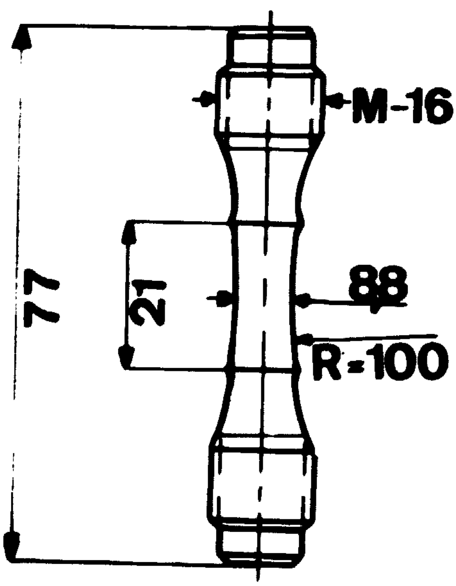


Fig. 2. Dimensions of the specimen

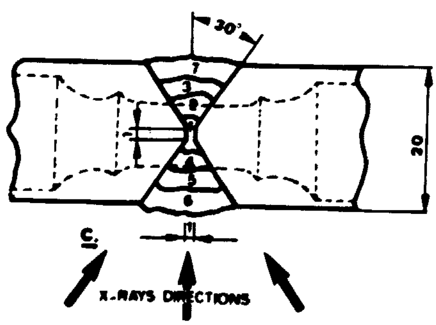


Fig. 3. Location of the specimen with respect to the weld layers.

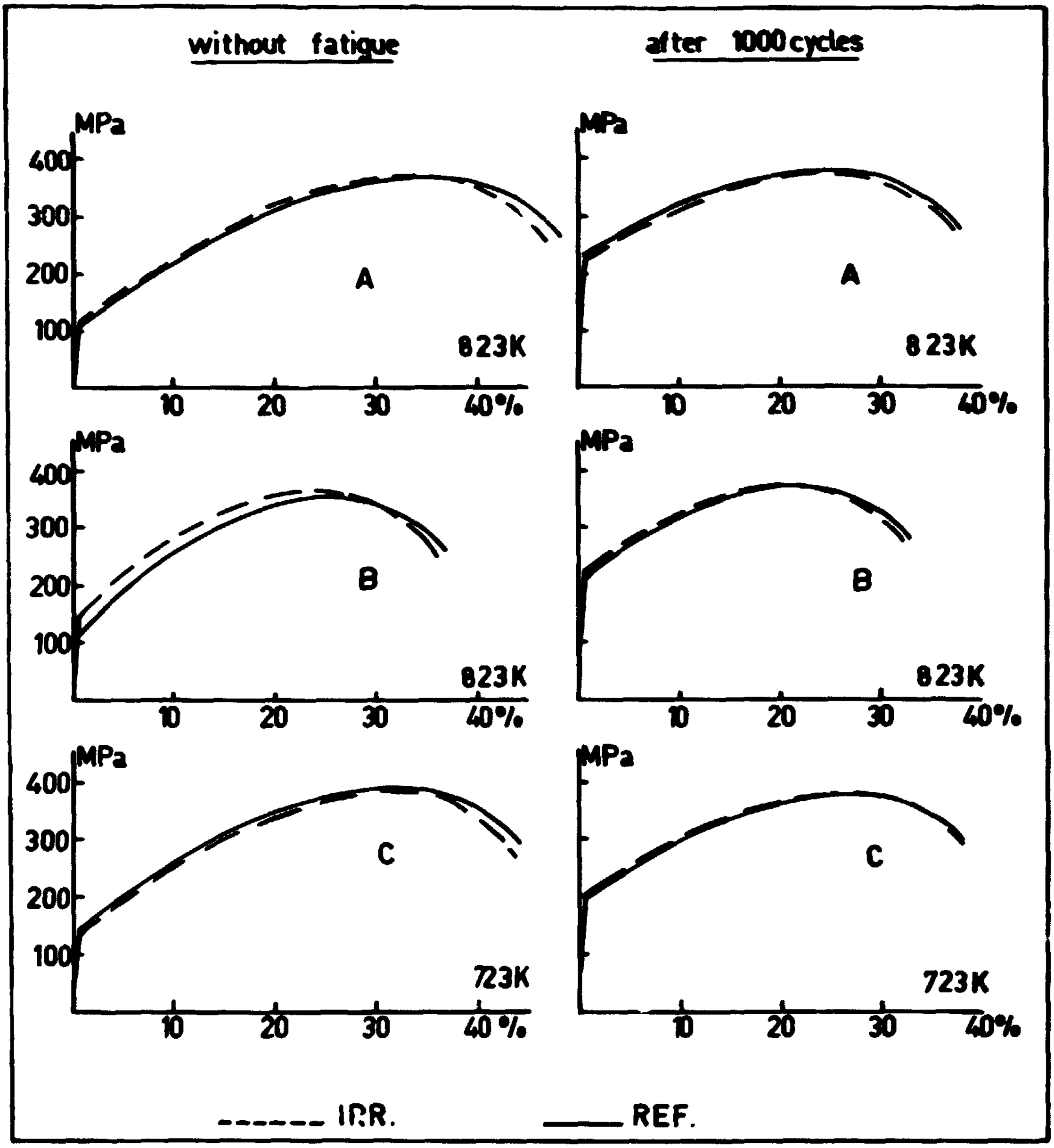


Fig. 4. High-rate ($\dot{\varepsilon}$ = 1 s^{-1}) tensile curves of irradiated and unirradiated plate metal DIN 1.4948 without and with prior fatigue loading.

A = irradiated, $1.10^{23} n.m^{-2}$ (E > 0.1 MeV) at 823 K or unirradiated reference, heat treated 24 hrs at 823 K.

B = irradiated, $5.10^{24} n.m^{-2}$ (E > 0.1 MeV) at 823 K or unirradiated reference, heat treated 456 hrs at 823 K.

C = irradiated, $5.10^{24} n.m^{-2}$ (E > 0.1 MeV) at 723 K or unirradiated reference, heat treated 456 hrs at 723 K.

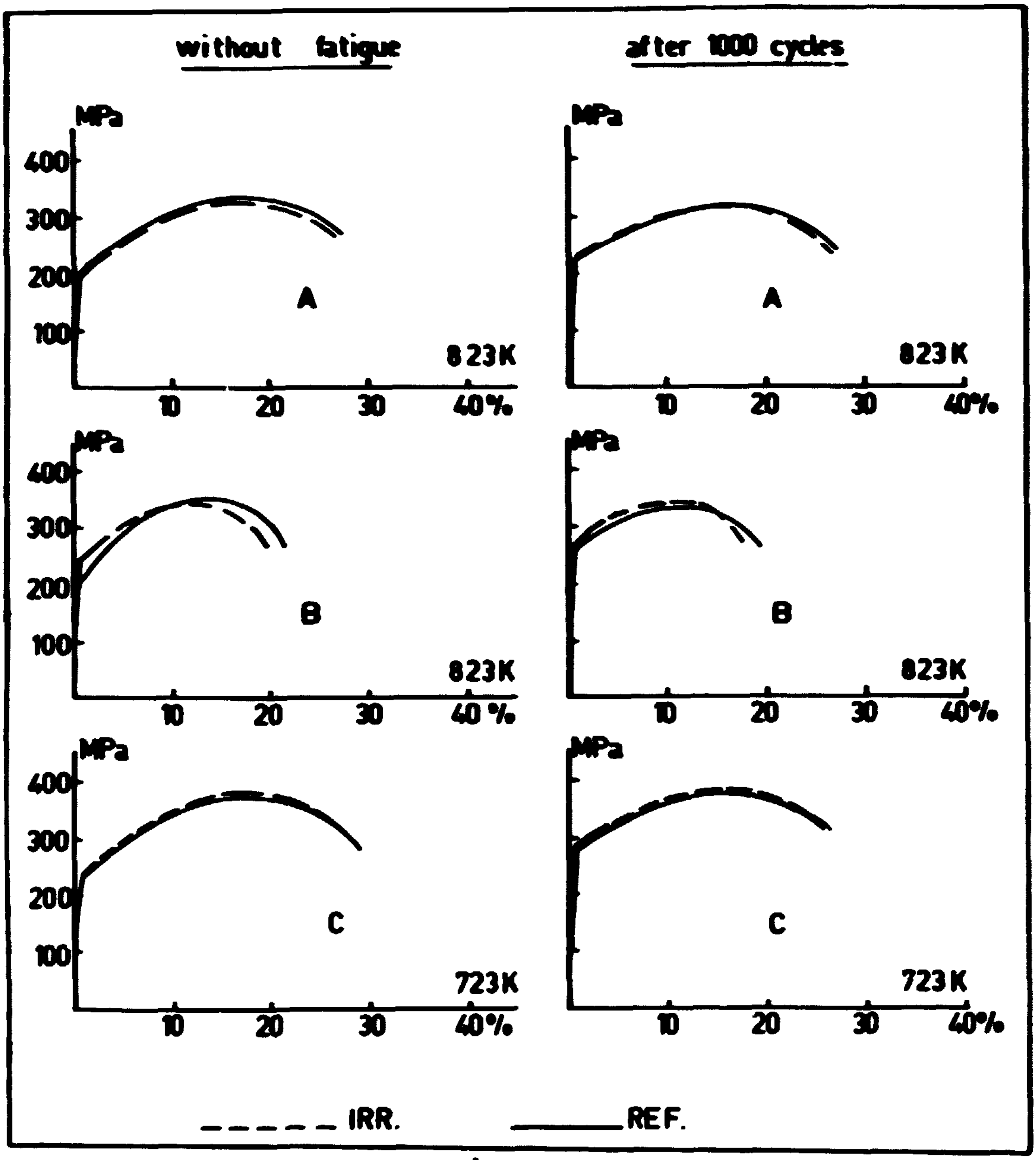


Fig. 5. High-rate ($\dot{\varepsilon}$ = 1 s^{-1}) tensile curves of irradiated and unirradiated welded joints DIN 1.4948 without and with prior fatigue loading.

A = irradiated, $1.10^{23} n.m^{-2}$ (E > 0.1 MeV) at 823 K or unirradiated reference, heat treated 24 hrs at 823 K.

B = irradiated, $5.10^{24} n.m^{-2}$ (E > 0.1 MeV) at 823 K or unirradiated reference, heat treated 456 hrs at 823 K.

C = irradiated, $5.10^{24} n.m^{-2}$ (E > 0.1 MeV) at 723 K or unirradiated reference, heat treated 456 hrs at 723 K.

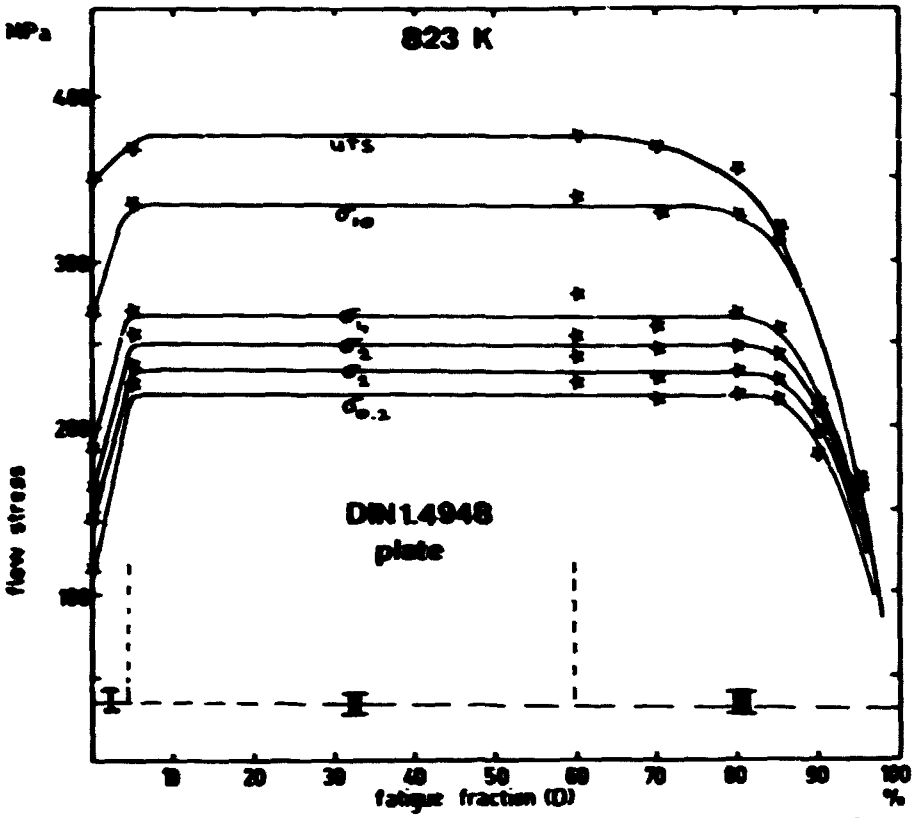


Fig. 6. High-rate flow stress values at increasing prior fatigue fraction. Stainless steel DIN 1.4948 plate metal at 823 K.

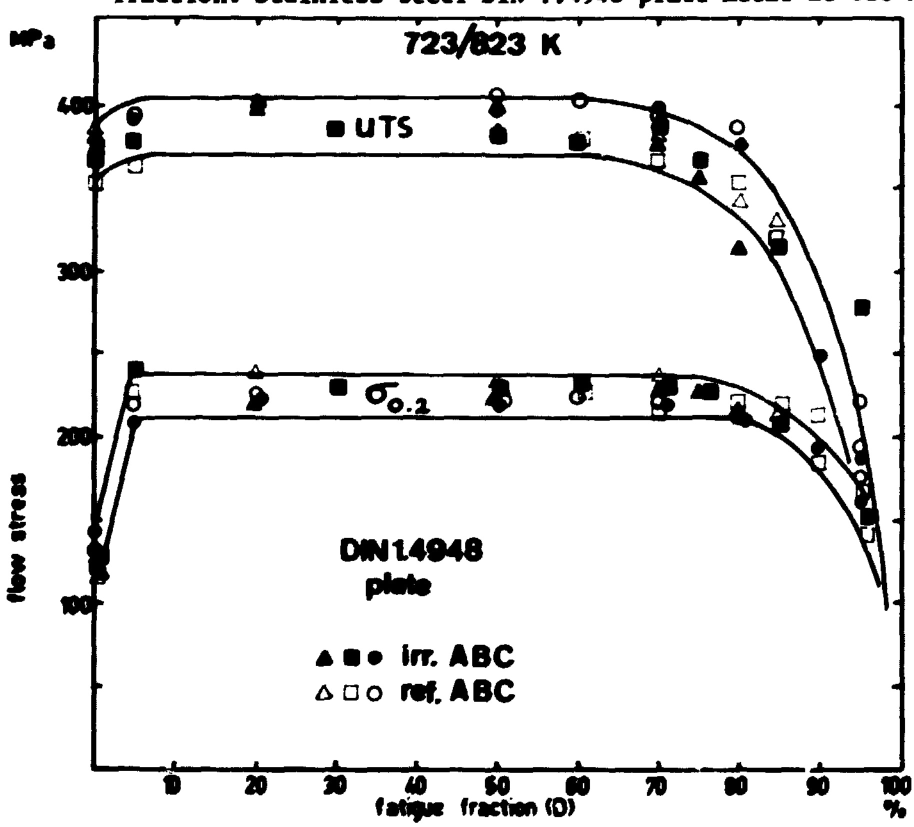


Fig. 7. High-rate tensile stress values at increasing prior fatigue fraction. Stainless steel DIN 1.4948 plate metal at 723 K and 823 K.

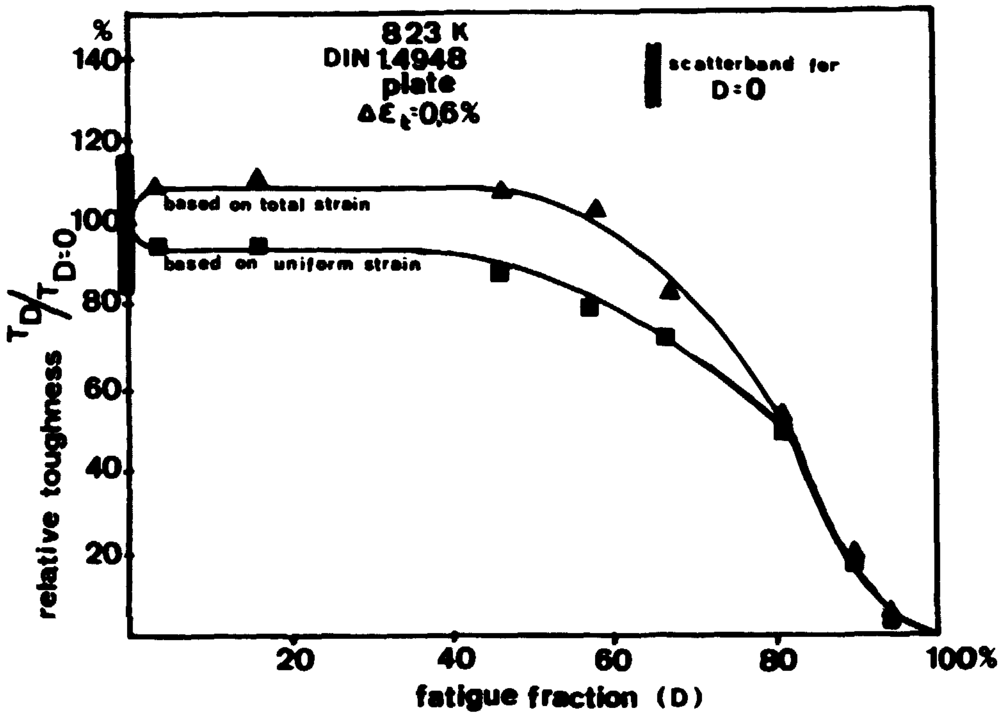


Fig. 12. Normalized toughness of plate metal DIN 1.4948 at 823 K at increasing prior fatigue fraction.

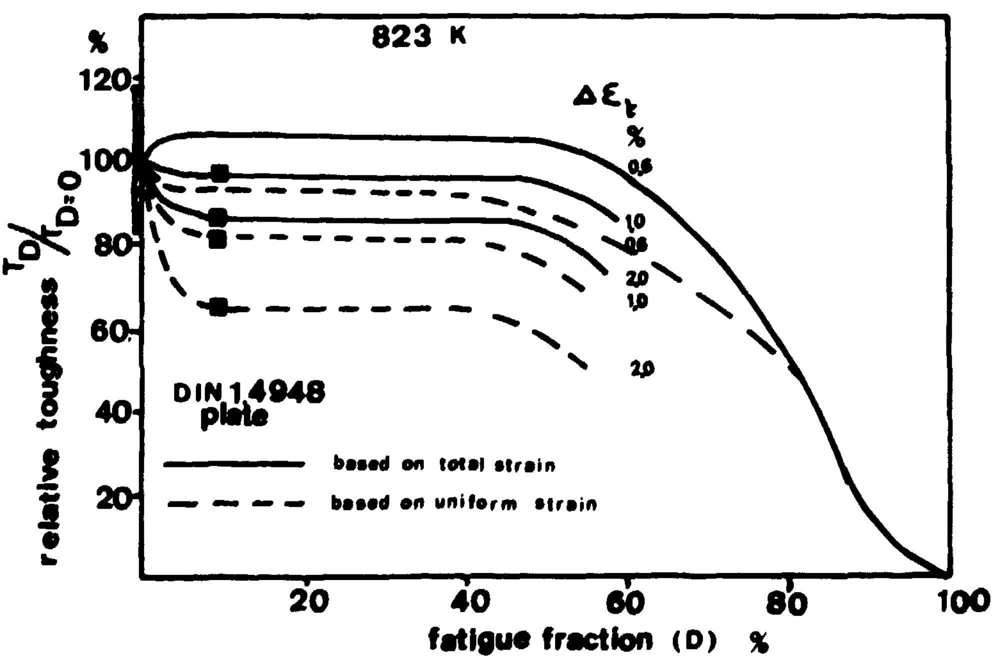


Fig. 13. Trend-curves of normalized toughness of plate metal DIN 1.4948 at 823 K after prior fatigue exposure at different strain ranges.

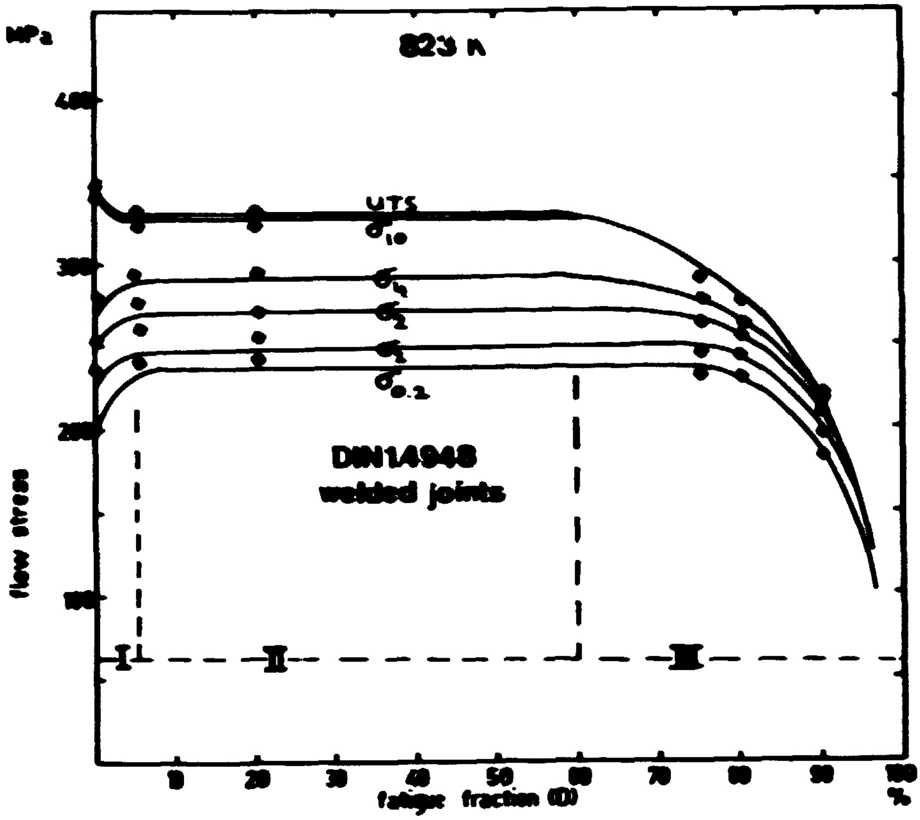


Fig. 14. High-rate flow stress values at increasing prior fatigue fraction. Welded joints DIN 1.4948 at 823 K.

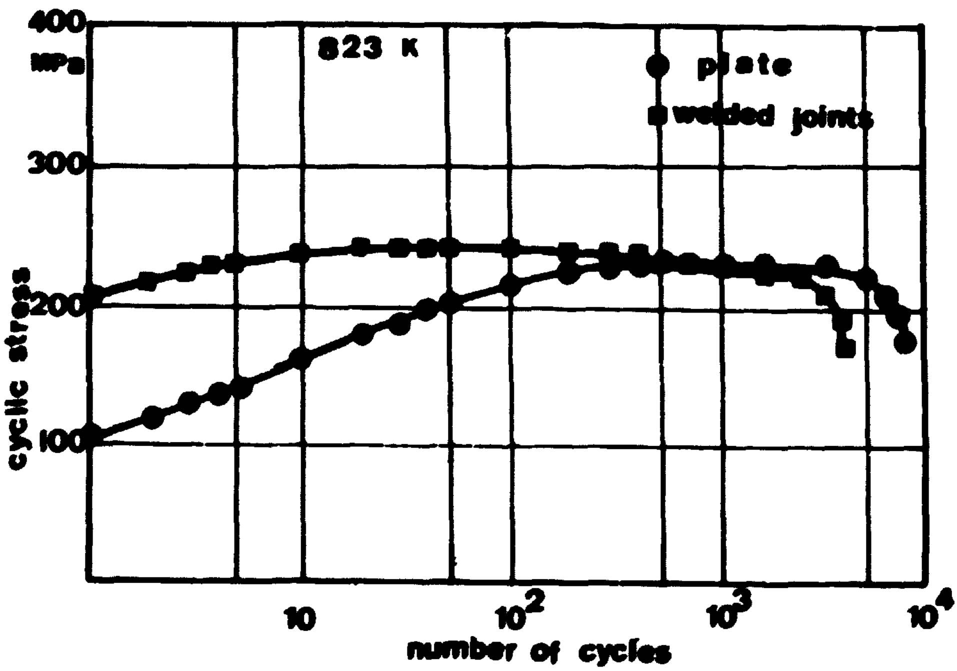


Fig. 15. Cyclic hardening of plate metal and welded joints DIN 1.4948 during low cycle fatigue testing at a strain range of 0.6% at 823 K.

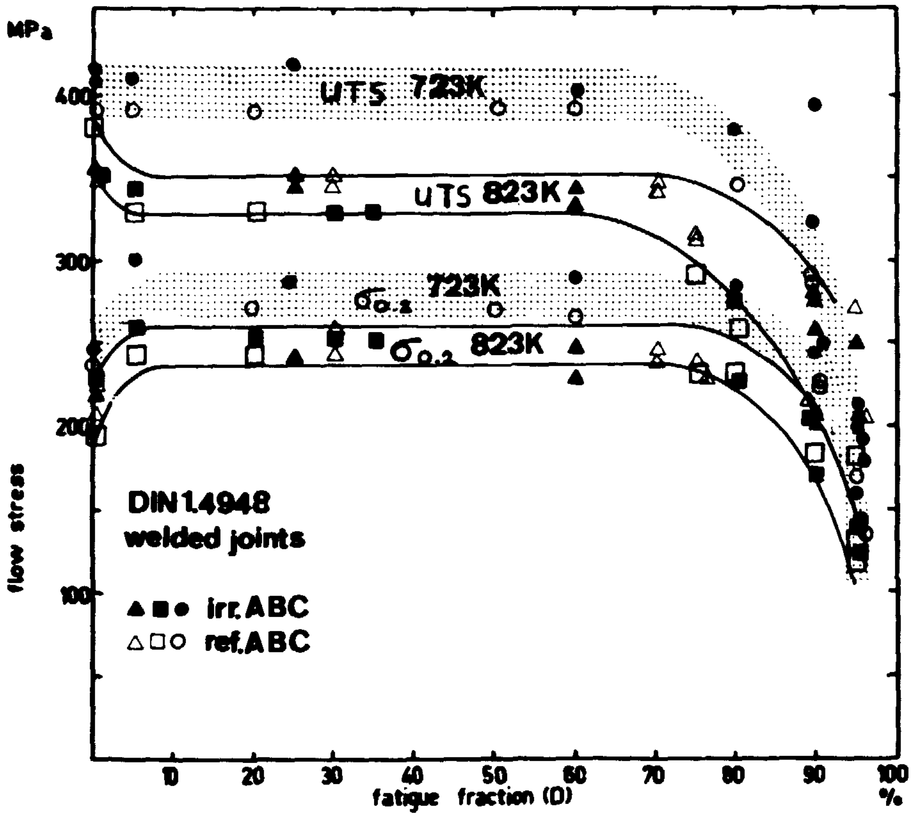


Fig. 16. High-rate tensile stress values at increasing prior fatigue fraction. Welded joints DIN 1.4948 at 723 K and 823 K.

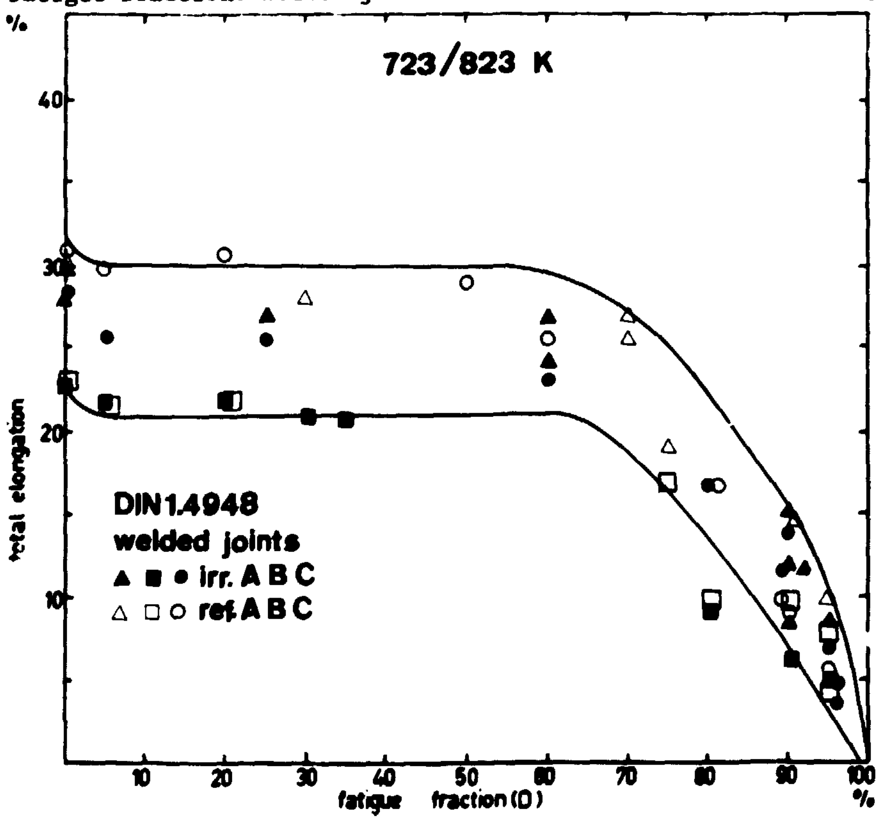


Fig. 17. High-rate total elongation values at increasing prior fatigue fraction.

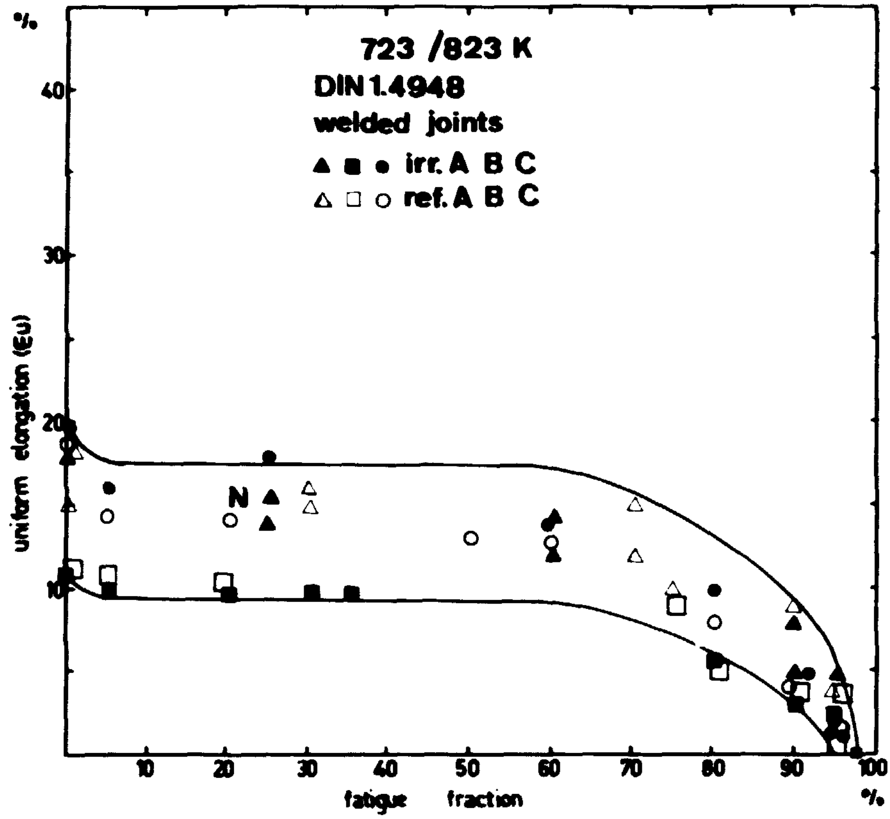


Fig. 18. High-rate uniform elongation values at increasing prior fatigue fraction.

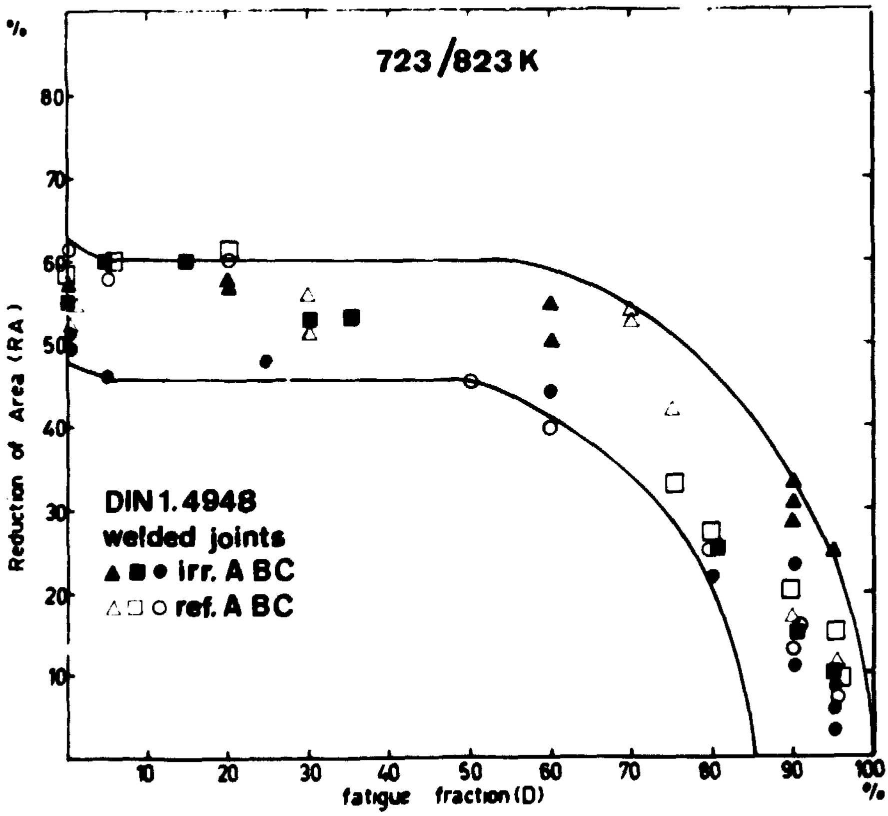
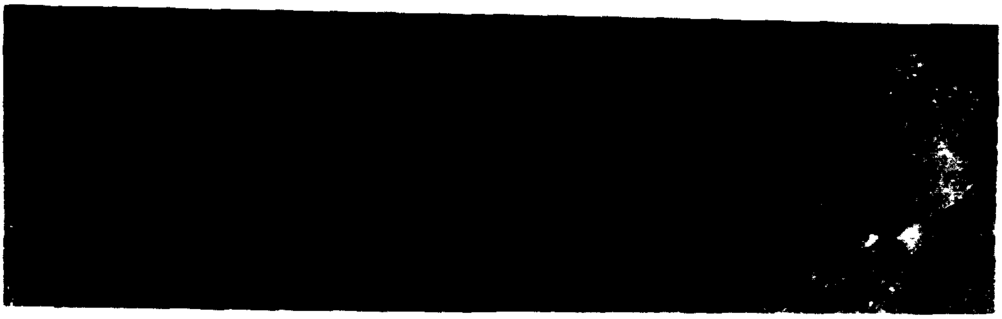


Fig. 19. High-rate reduction of area (RA) values at increasing prior fatigue fraction.



a

b

Fig. 20. Showing: a) decoration of dislocations after irradiation up to 5.10^{24} n.m^{-2} at 823 K. The same features are seen in 723 K specimens.

b) low density of small He-bubbles after irradiation at 823 K up to 5.10^{24} n.m^{-2} (E > 0.1 MeV).

Fig. 21. Dislocation substructure of plate metal DIN 1.4948 in the as-fabricated condition.

Fig. 22. Dislocation substructure of plate metal DIN 1.4948 after fatigue loading only (strain range 0.6% at 823 K).

Fig. 23. Dislocation substructure of plate metal DIN 1.4948 after fatigue loading and tensile testing at 823 K.

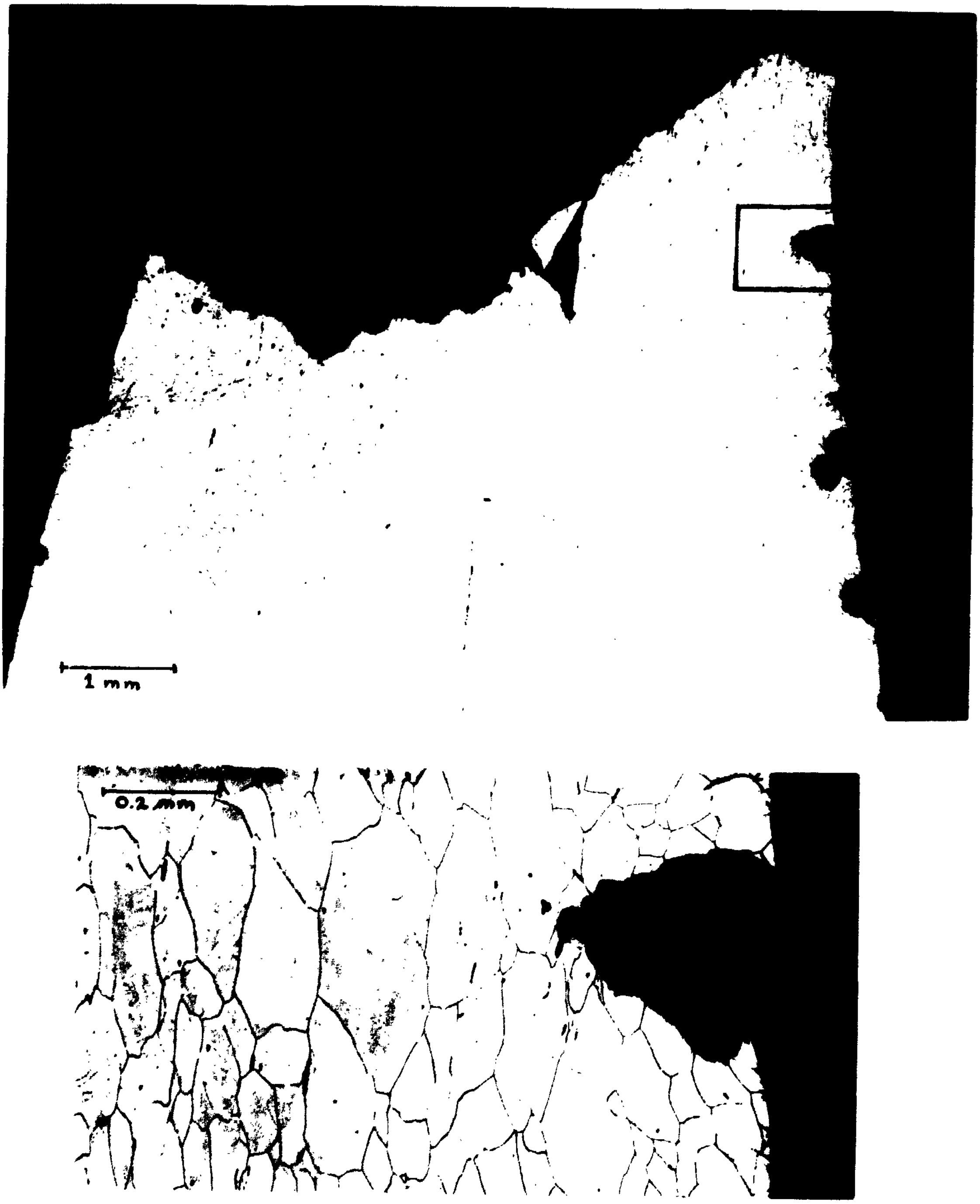


Fig. 24. Optical micrographs of tensile tested plate metal DIN 1.4948 after prior fatigue up to 70% of fatigue life, showing openend surface cracks.

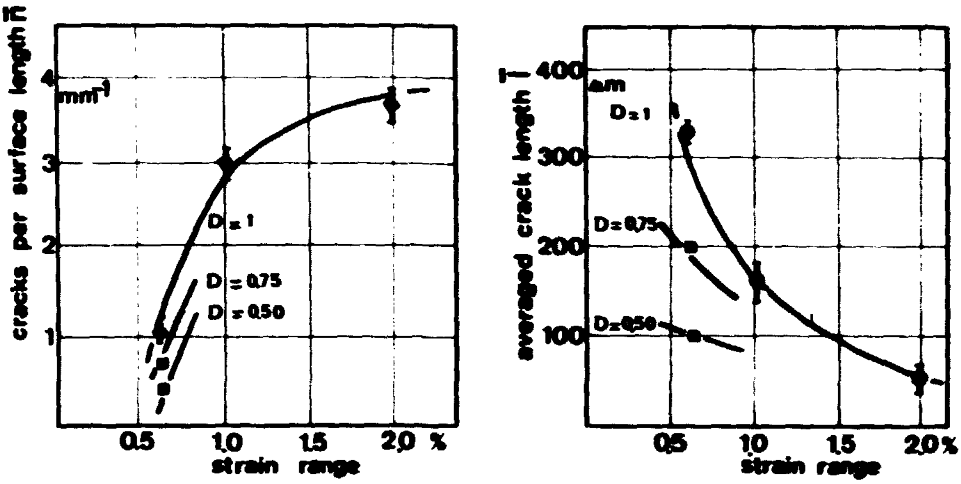


Fig. 25. Crack density ($\bar{n}$) and crack length ($\bar{l}$) as measured after prior fatigue up to D = 0.50 and 0.75, compared with results after fatigue to failure (D = 1) from [3].

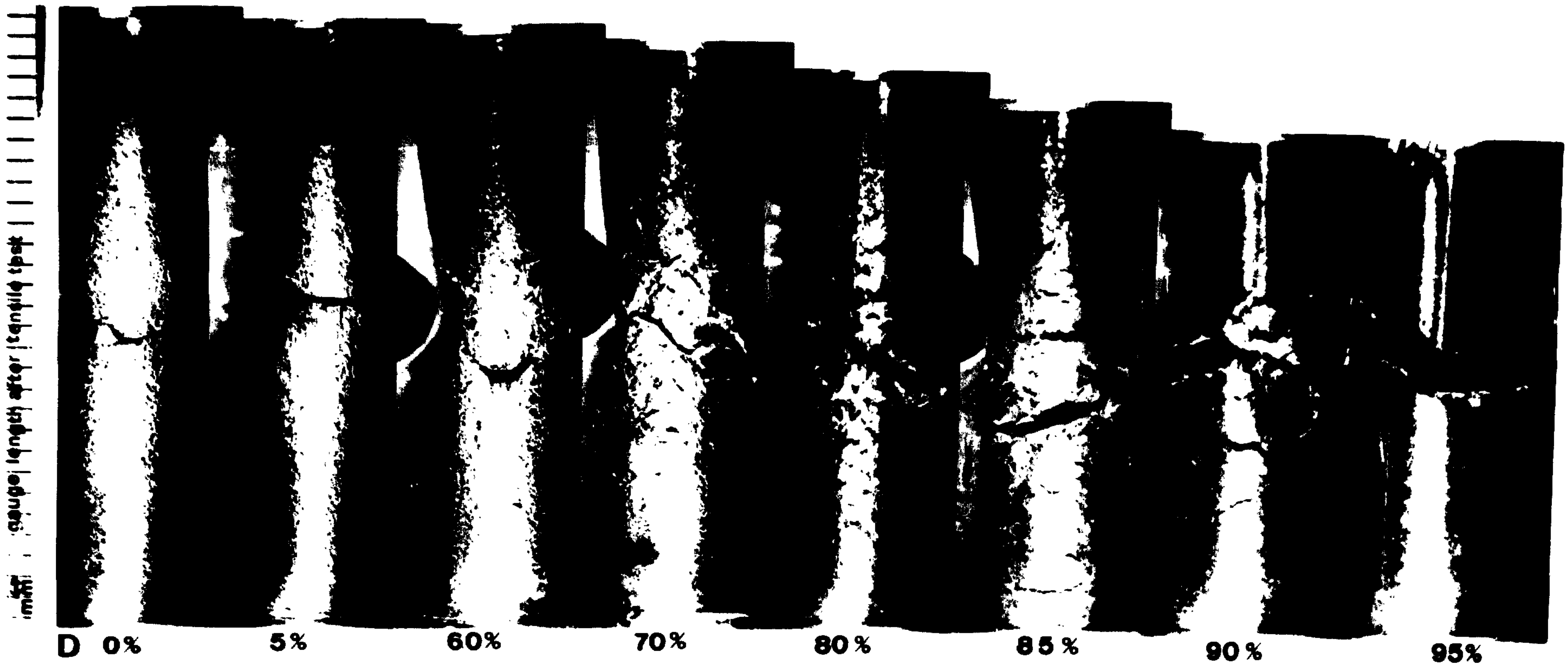
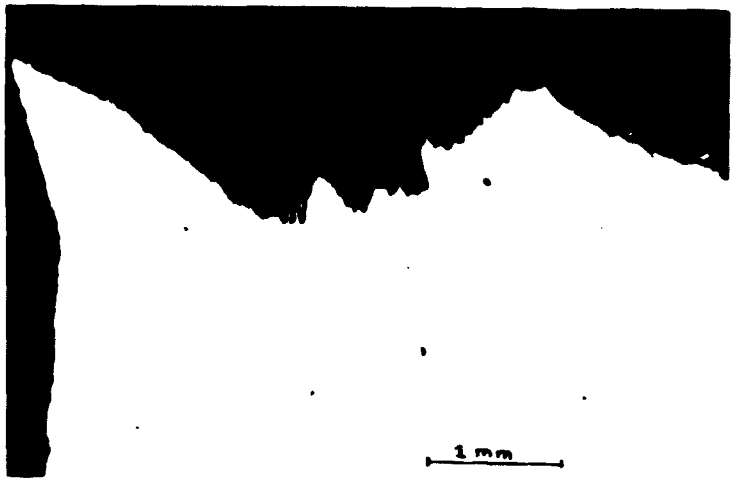
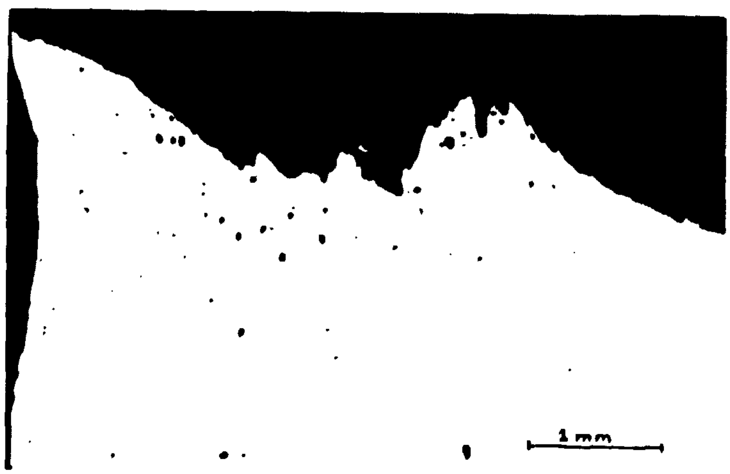


Fig. 26. Series of broken parts of tensile tested plate metal DIN 1.4948 arranged at increasing prior fatigue (D).



a

total elongation 46%



b

total elongation 37%

Fig. 27. Comparison of tensile tested specimens with high- (46%) and low value of total elongation (37%), showing considerable voidage from inclusions in the latter.

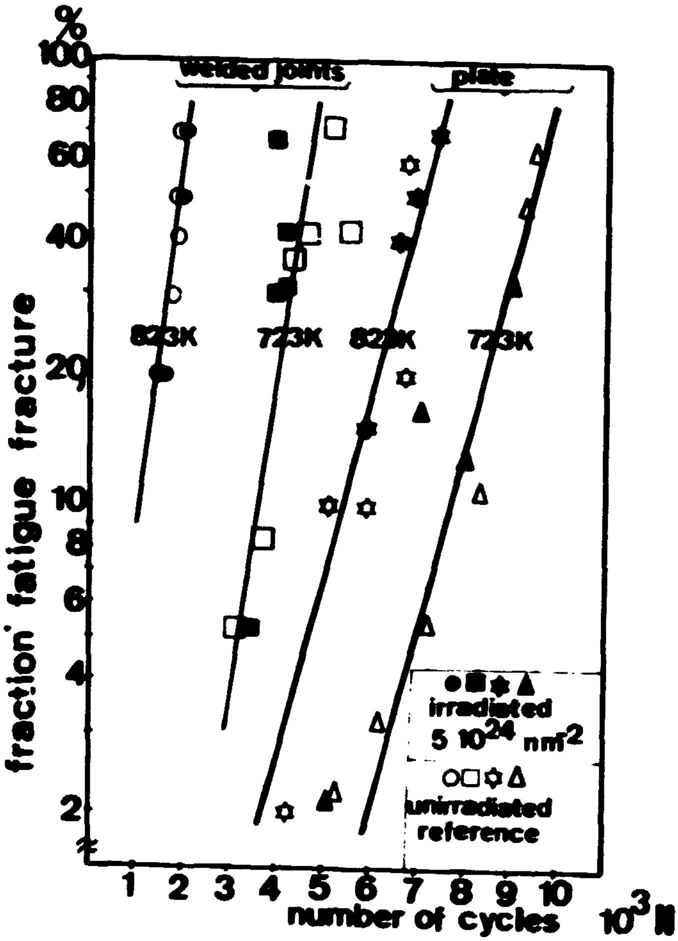


Fig. 30. Fraction of fracture surface occupied with fatigue fracture versus the number of applied prior fatigue cycles.

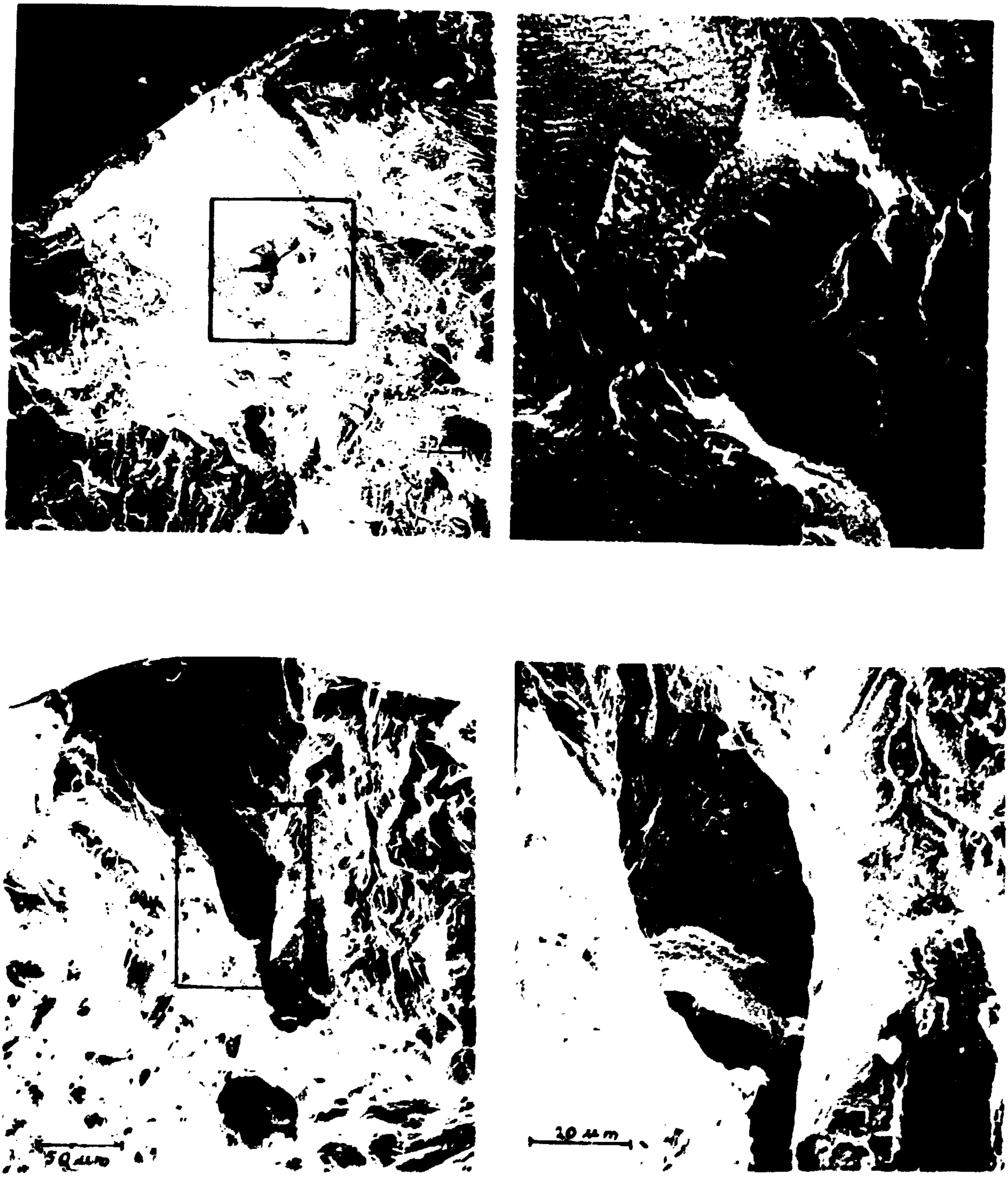


Fig. 31. Local intergranular fracture of isolated grains on the fracture surfaces of specimens irradiated at 823 K.

Fig. 32. Fracture surface of plate metal DIN 1.4948 tensile tested after 6000 prior fatigue cycles. Note the area around the outer surface, occupied by fatigue fracture and the secondary cracks due to inclusions in the tensile part of the fracture surface.