MICROSTRUCTURE AND FRACTURE MECHANISMS IN A HIGH STRENGTH LOW - ALLOY MARTENSITIC STEEL

G. Zouhar jr., M. Schaper, J. Eickemeyer and P. Finke

Academy of Science of the GDR, Central Institute of
Solid State Physics and Materials Research, Dresden

ABSTRACT

Relations between microstructure and mechanical properties of a high strength thermomechanically treated martensitic 0,5% - 1%Cr - 0,1%V -steel are examined after tempering at low temperature. To investigate the role of minor impurities two material qualities containing different amounts of minor elements are compared. Strength, fracture toughness and stress corrosion cracking threshold were analysed in relation to microstructural features and local failure mechanisms. From the results it is concluded, that the content and the distribution of minor impurities in connection with recovery and recrystallization processes in the stable austenite control the fracture behaviour of the martensite. Thus in selection of deformation-temperature-time-regimes for HTMT not only grain refinement and dislocation structure in the stable austenite and their inheritance to the martensite have to be considered. Other metallurgical variables like minor impurities may have an overwhelming effect on toughness properties.

KEYWORDS

Martensitic steels; minor impurities; thermomechanical treatment; fracture toughness; stress corrosion cracking; fracture mechanisms.

INTRODUCTION

It is well known, that strength and toughness of high strength martensitic steels may be enhanced simultaneously by high temperature thermomechanical treatment (Bernštejn, 1968; Kula, 1978). Responsible for this effect is the favourable combination of various hardening mechanisms. But there are no systematic investigations on the relations between the degree of recrystallization of the austenite and the resulting mechanical properties. Furthermore the influence of minor impurities and aggressive environments is not clear. In this paper results about the influence of the degree of recrystallization on strength, toughness and stress corrosion cracking behaviour of a high strength martensitic 0,5% - 1%Cr - 0,1%V -steel are presented. To take out possible effects of minor impurities on the fracture toughness and the stress corrosion cracking threshold two steel qualities with different purity levels of the base material are examined.

EXPERIMENTS

The chemical composition of the Cr-V-steel used during this investigation is shown in Table 1. The abbreviation CP stands for the arc-melted material of commercial purity.

TABLE 1 Chemical Composition of the Cr-V-Steel 50CrV4 (m-%)

Material	C	Si	Mn	P	S	Cr	V	Cu	Ni
CP	0,49	0,33	0,78	0,023	0,016	0,90	0,11	-	-
HP	0,53	0,31	0,75	0,004	0,004	0,94	0,11	0,02	0,04

- not determined

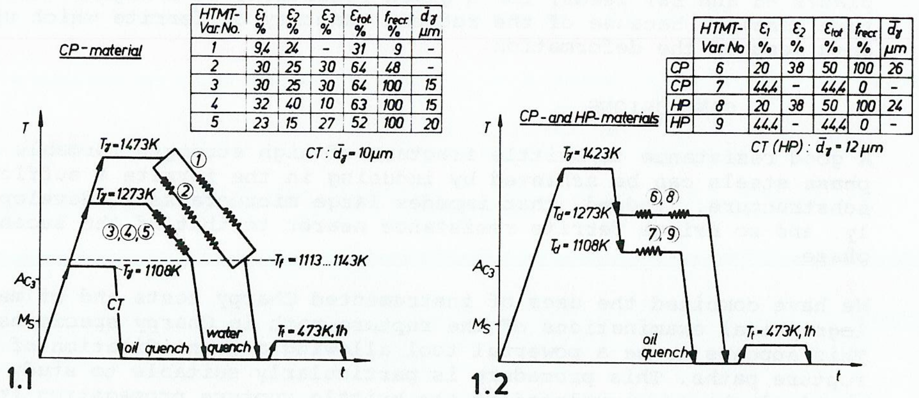
The HP quality was melted in a 10kg-vacuum induction furnace from high-purity base material. Microstructure, size and elongation of the prior austenite grains especially the percentage of fine grain recrystallized austenite are varied by:

- conventional heat treatment (CT)
- high temperature thermomechanical treatment (HTMT) including single and multiple pass rolling.

The rolled and forged billets of 37 and 30 mm thickness were rolled down to 20, 10 and 6,5 mm in the deformation-temperature-time-regimes illustrated in Fig. 1. The nearly constant finishing temperature T_f of the HTMT 1 - 5 has been realised by choosing different cooling times between the end of the austenitizing treatment and the start of hot rolling. With respect to the HTMT 6 - 9 step cooling down to the nearly constant deformation temperatures T_d has been used. Immediatly after rolling the material was quenched in water or oil, followed by a tempering treatment at 473 K, 1 h. The CT indicated in Fig. 1.1. was applied to both the CP and the HP material.

Typical prior austenite grain structures achieved are shown in Fig. 2 for the CP material. Possibly due to the lower trace element concentrations the prior austenite grain boundaries of the HP material were less clearly revealed by etching. The average grain diameter of the HTMT-conditions 3 - 6 and 8 and the percentage of the recrystallized fine grained prior austenite were quantitativly determined in sections perpendicular to the rolling direction. The results are indicated in the tables included in Fig. 1. The in rolling direction elongated prior austenite grains obtained after HTMT 1,2,7,9 contain a polygonized dislocation structure, which is inherited to the martensite. The martensitic structure consists mainly of lath martensite.

The specimens for tensile tests were prepared with their axis parallel to the rolling direction. The orientation of the fatigue precrack for the fracture mechanics SEN bending specimens has been at right angles both to rolling direction and plane. The threshold of stress corrosion cracking K_{ISCC} was measured in a saturated $Ca(OH)_2 + CaSO_4$ solution ($p_H = 12{,}5$). Details of the test method are published elsewhere (Eickemeyer, 1974). All teste were conducted at room temperature.



HTMT-Var.No.	ε_1 %	ε_2 %	ε_3 %	ε_{tot} %	$f_{recr.}$ %	$\bar{d}_\gamma$ µm
1	9,4	24	-	31	9	-
2	30	25	30	64	48	-
3	30	25	30	64	100	15
4	32	40	10	63	100	15
5	23	15	27	52	100	20

	HTMT-Var.No	ε_1 %	ε_2 %	ε_{tot} %	f_{recr} %	$\bar{d}_\gamma$ µm
CP	6	20	38	50	100	26
CP	7	44,4	-	44,4	0	-
HP	8	20	38	50	100	24
HP	9	44,4	-	44,4	0	-

Fig. 1. Temperature-time -diagrams for the heat treatments applied. Fig. 1.1.- CT and HTMT 1 - 5, Fig. 1.2.- HTMT 6 - 9. The ε denote the reduction in cross sectional area respectively. $f_{recr.}$ - percentage of recrystallized fine grained prior austenite. $\bar{d}_\gamma$ - average diameter of prior austenite grains.

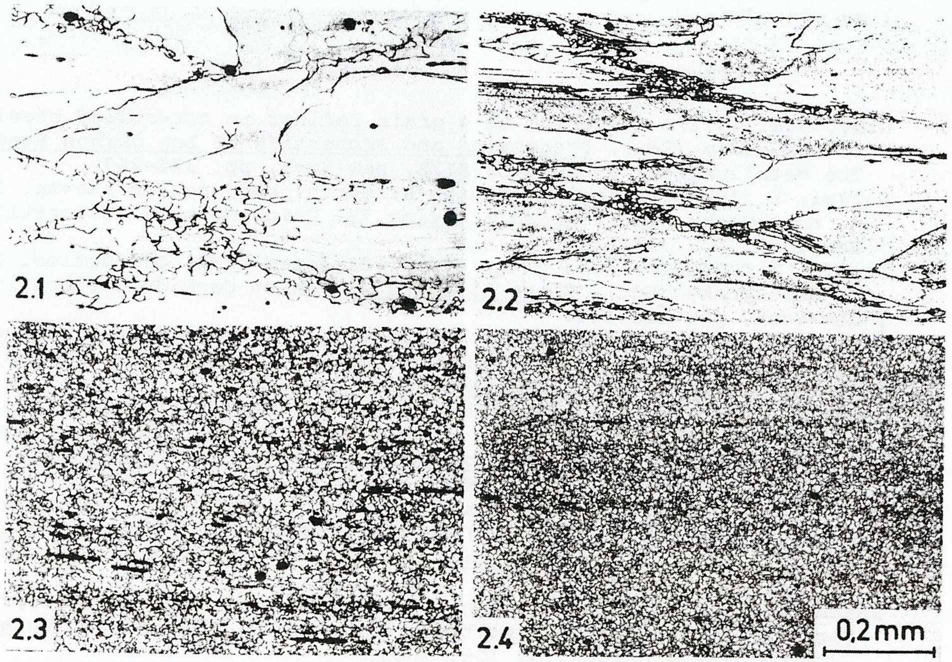


Fig. 2. Typical prior austenite structures of the Cr-V-steel, CP material, longitudinal sections. Fig. 2.1.- HTMT 1, Fig. 2.2.- HTMT 2, Fig. 2.3.- HTMT 3 and 4, Fig. 2.4.- CT.

RESULTS AND DISCUSSION

The fracture toughness-yield stress relations resulting from HTMT and CT are summarized in Fig. 3 for both material qualities. Obviously the fracture toughness can be enhanced significantly by HTMT, whereas the increase in strength is comparatively small. Moreover a pronounced effect of purity is evident, the K_{IC} values being higher for the HP than for the corresponding CP conditions.

With regard to the HTMT effect a strong dependence of the fracture toughness on degree of recrystallization is observed, especially for the CP material (Fig. 4). High values of K_{IC} are measured for the at most partially recrystallized conditions 1, 2 and 7, provided that the portion of fine grained prior austenite is less than about 50 per cent. In the nearly completely unrecrystallized condition 1, which is characterized by only slightly stretched large γ-grains, intercrystalline fracture prevails, both the intense crack deviations and a comparatively high grain boundary strength being responsible for the relatively high K_{IC} value. In the microstructures 2 and 7, containing heavily stretched prior austenite grains, fracture proceeds by decohesion of the γ-grain boundaries, a crack divider type process, combined with localized transcrystalline shear(Fig. 5). The shear surfaces are covered with microvoids, which indicates a void sheet mechanism. This fracture mode and the corresponding high K_{IC} values are promoted by internal stresses resulting from the geometry of the deformation zone during hot rolling. With respect to the rolling direction there are tensile stresses near the surfaces but compression stresses in the interior of the plate. For the type of specimens under consideration these internal stresses modify the stress field near the crack tip in such a way, that the σ_{yy} component acting in loading direction is reduced, whereas the through - thickness component σ_{zz} is increased. From the first argument it follows, that plastic de-

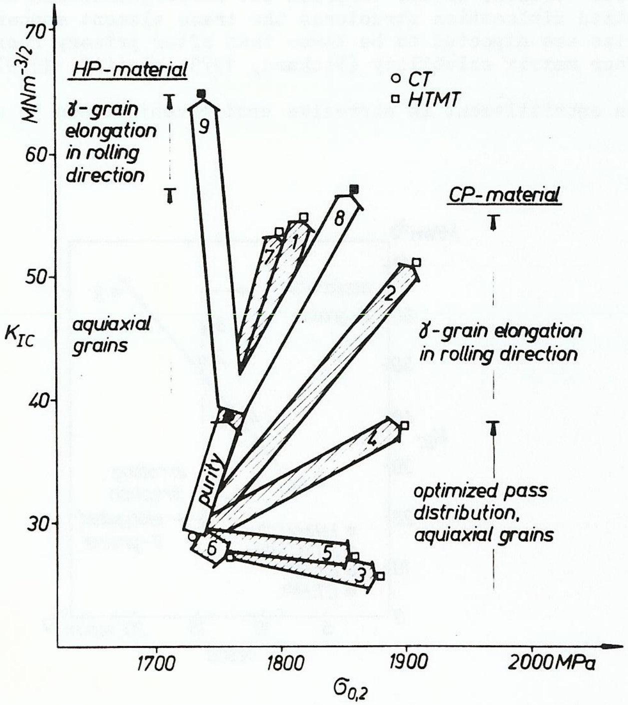


Fig. 3. Fracture toughness versus 0,2 per cent yield stress for the Cr-V-steel tempered at 473 K. The numbers within the arrows refer to the investigated HTMT conditions, see Fig. 1.

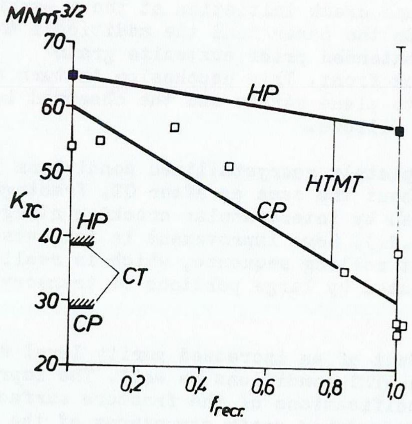


Fig. 4. Fracture toughness of the Cr-V-steel in relation to the percentage of the fine grain recrystallized prior austenite. The material conditions corresponding to the data points at 0,32 and 0,84 are not discussed in this paper.

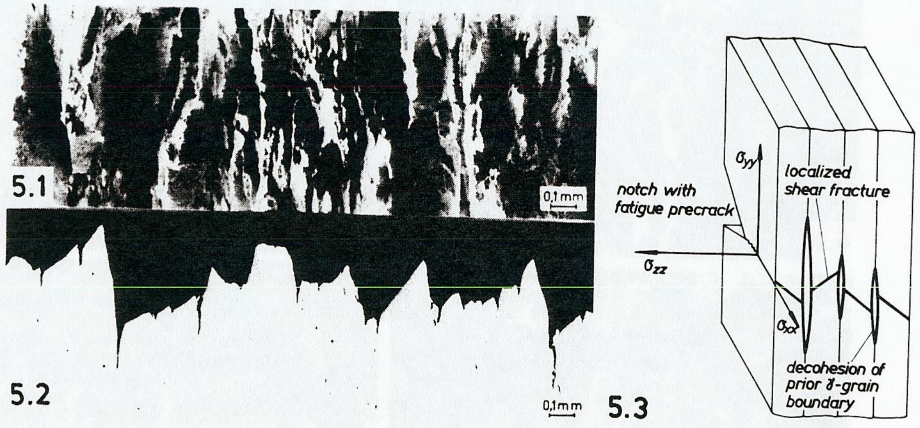


Fig. 5. Fracture mechanism for the only partially recrystallized condition, HTMT 2, with elongated prior austenite grains. Fig. 5.1.- fracture surface, Fig. 5.2.- fracture profile, Fig. 5.3.- mechanism, schematic.

formation and perhaps crack initiation at the γ-grain boundaries needs higher applied K levels. On the other hand the additional σ_{zz} component supports the decohesion of the extended prior austenite grain boundaries lying perpendicular to the crack front. This decohesion in turn alters the near tip field from plane strain to plane stress and the observed localized shear in the y - z plane immediatly follows.

For the almost completely recrystallized conditions 3, 5 and 6 the K_{IC} values are very low and about the same as after CT. Fractography revealed, that the specimens had failed by intergranular cracking along the prior austenite grain boundaries (Fig. 6.1.). Some improvement in toughness is attainable by an optimization of the hot rolling sequence, which is realized with HTMT 4. The higher toughness is reflected by large portions of transcrystalline dimple-type fracture (Fig. 6.2.).

The beneficial effect of an increased purity level shown in Fig. 3 is observed for the CT and the HTMT conditions as well. The improved fracture resistance correlates with modifications of the fracture surface morphology. In the high toughness heavily stretched grain structures of the HP material (HTMT 9) the crack grows by the same mechanism as in the corresponding CP condition 7.

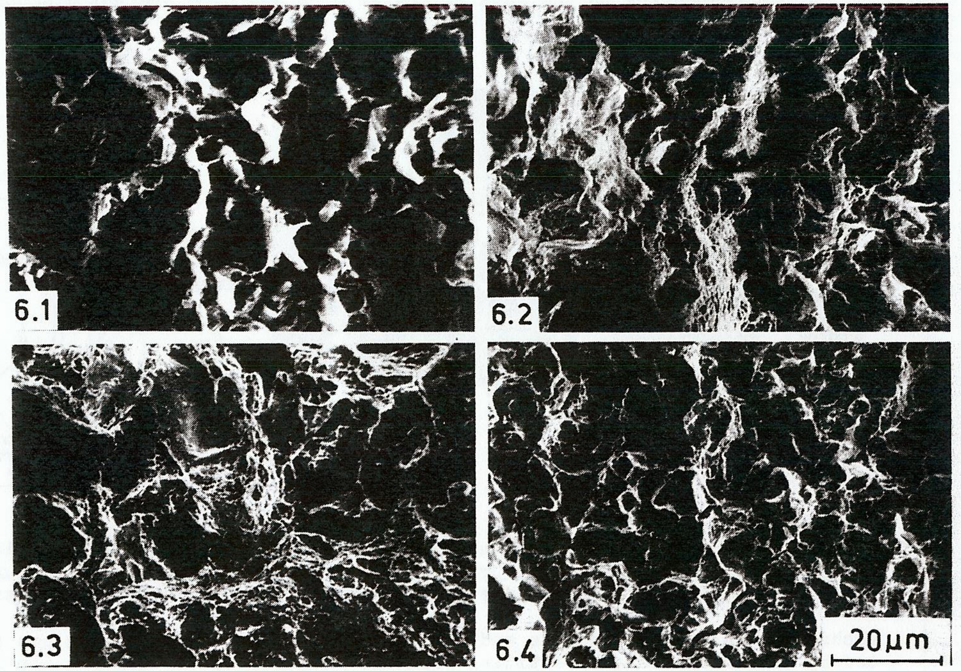


Fig. 6. Scanning electron micrographs of fine grained prior austenite structures showing Fig. 6.1. - entirely intercrystalline brittle fracture for HTMT Fig. 6.2. - larger portions of dimple-type fracture for HTMT 4, Fig. 6.3 - almost entirely transcrystalline plastic fracture in the HP material, HTMT 8, Fig. 6.4. - primarily intercrystalline seperation in the finer grained CT condition of the CP material.

Higher energy dissipation is reflected by the voids on the shear surfaces being larger in the HP material. This implies higher matrix deformations prior to decohesion. Additionally an increased grain boundary strength is to be assumed. In the completely recrystallized condition of the HP material (HTMT 8) transcrystalline plastic fracture prevails (Fig. 6.3.). This is in marked contrast to the intercrystalline brittle fracture observed for the corresponding HTMT 6 of the CP material (compare Fig. 6.1.).

From the above mentioned results it follows, that alterations in grain boundary strength are at least partly responsible for the influence of HTMT procedures and purity level on K_{IC}. It is expected ,that for the conditions at hand grain boundary segregations of substitutional elements like phosphoric and their interaction with copper and vanadium are of concern (Wieting, 1979). Sulfur should be bound to manganese and chromium. Obviously grain boundary embrittlement is responsible for the low K_{IC} values of the CP conditions containing a high portion of recrystallized fine grained prior austenite. Due to quenching immediatly after hot rolling the enrichments at the austenite grain boundaries are inherited to the martensite. Tempering at 473 K has no effect in altering this situation. With respect to the HTMT 4 it is assumed, that the recrystallization is influenced by the applied hot rolling procedure in such a way, that the enrichment is partly suppressed and the grain boundary weakening is reduced. Lattice defects introduced by the comparatively low plastic deformation applied during the last pass are certainly not efficient with respect to recrystallization but increase the matrix solubility, and some purification of the grain boundaries results. In the deformed but unrecrystallized austenite containing polygonized dislocation structures the trace element concentrations at the grain boundaries are expected to be lower than after primary recrystallization due to the higher matrix solubility (Pichard, 1975; Wieting, 1979).

Hydrogen embrittlement in corrosive environments leads to stress corrosion

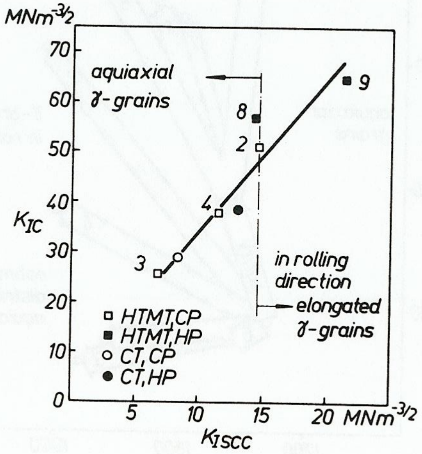


Fig. 7. Correlation between fracture toughness and stress corrosion cracking threshold measured in a saturated $Ca(OH)_2 + CaSO_4$ solution. The numbers refers to the investigated HTMT conditions, see Fig. 1.

cracking threshold K_{ISCC} which are found to be about one third of the fracture toughness irrespective of the material purity and the hot rolling procedure. The increase in K_{IC} from 26 $MNm^{-3/2}$ to 65 $MNm^{-3/2}$ corresponds to an increase of the K_{ISCC} values from 7 $MNm^{-3/2}$ to 21,5 $MNm^{-3/2}$ (Fig. 7). As for the fracture toughness the K_{ISCC} values of the elongated prior austenite grain structures are significantly higher than in the highly recrystallized material. As discussed above the presence of internal macrostresses and the lower grain boundary concentration with respect to embrittling elements favour this effect. Furthermore it is well known, that the embrittling effect of hydrogen is increased by the presence of elements like phosphoric in steels (Banerji, 1978). Therefore the higher K_{ISCC} values in the HP material are not surprising. This purity effect alone amounts to about 50 per cent in terms of K_{ISCC} for the CT as well as the HTMT material. These results clearly demonstrate a remarkable influence of the prior austenite structure as well as the purity level on the stress corrosion cracking threshold.

CONCLUSIONS

1. Grain refinement of the prior austenite by HTMT can result in intercrystalline brittle fracture in the K_{IC}-test and comparatively low K_{IC} values. It is suggested, that critical enrichments of minor elements at the austenite grain boundaries appear during primary recrystallization. If this enrichments are inherited to the martensite by quenching they lower the cohesion of the prior austenite grain boundaries.

2. The fracture toughness may be markedly increased at nearly the same strength level by controlled recrystallization of the austenite and by increasing the purity level with respect to minor elements. This also applies to hydrogen embrittlement in corrosive environments. Between the K_{IC} and the K_{ISCC} a nearly constant 3 : 1 relation has been found for all the investigated conditions.

3. Irrespective of the purity level the highest toughness values are measured both in partly recrystallized microstructures containing higher amounts of unrecrystallized elongated prior austenite grains and in completely unrecrystallized prior austenite grain structures.

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