BIII-9 Relation between steel purity and tensile, creep and fatigue properties

A. Buch*

Abstract.

In this investigation a study has been made of the influence of inclusion type, forging ratio and heat treatment on the properties of long. and trans. specimens. It was shown, that in case of the same kind of steel with the same inclusion type, forging ratio and tensile strength, the material with smaller transverse ductility and fracture strength contains more large non-metallic inclusions and has in general worse fatigue properties. The relation between steel impurity and mechanical properties was studied for Cr-, Cr-Ni-Mo-, and Cr-Ni-V-steels from conventional and electrode consumable melts.

1. Introduction.

According to numerous investigations the anisotropy of steel plasticity properties first of all depends on the degree of impurity, on the forging ratio and tensile strength. The dependence of the anisotropy of plasticity on the purity may be taken into account while selecting billets, forgings and machine parts from the viewpoint of material quality. As it is well known a high degree of material purity increases the fatigue strength and decreases the danger of brittle fracture. This is of significant importance in case of machine parts under high fatigue load (e.g. crankshafts), for elements requiring good properties in transverse direction (e.g. high pressure piping) and also when cracking of elements during forging or heat treatment might occur.

2. Effect of steel purity on basic mechanical properties.

The degree of steel impurity does not influence the mechanical properties of specimens taken along the fibre. Simultaneously it distinctly affect the reduction of area, elongation and fracture stress of transverse specimens. This is illustrated in Fig.1 which gives the comparison of mechanical properties of transverse specimens of CrNiMo steel of various purity. From Fig.1 it is evident that the reduction of area Z, the elongation A_5 and the fracture stress R_u are less for the steel of greater nonmetallic inclusion content.

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* Doctor of Mechanical Engineering. Head of the Strength Research Laboratory in Instytut Mechaniki Precyzyjnej, Warsaw, Poland.

The purity of steel significantly affects the transverse reduction of area. This effect is greater when the tensile strength of the material is higher. That is shown explicitly in Fig.1.

According to our investigations (2) of CrNiMo-steel a good was found between the degree of material impurity estimated by means of metallographic determination of the relative area of inclusions in the transverse micrograph and the value of anisotropy ratio of reduction of area. The results of this investigations are shown in Table I.

As seen from Table I the anisotropy ratio of materials A_2 and B_2, with greater impurity, is below 0.5 and their fatigue strength is smaller. The impact strength of transverse specimens of the worse material is also a little smaller, however the difference is not so evident as in the case of transverse reduction of area.

When considering the anisotropy ratio of reduction of area of materials A_1 and B_1, their purity being sufficient, it may be found that the value of this ratio exceeds 0.5. In material B_1 with greater forging ratio (43:1) the value of the anisotropy ratio is somewhat lower (i.e. the anisotropy is greater) as compared with material A_1 with a lower forging ratio (8.5:1).

On the basis of data from Table II it may be concludet that the influence of the change of impurity degree is greater than the influence of the change of the forging ratio. A similar conclusion may be drown measurements for melts of CrNiMo-steel, as shown in Table II. As seen from Table II the anisotropy ratio value of materials, with the same forging ratio, differs by about 0.4, which is conneceted with the greater content of inclusions in melts Nr.3 and 12. No influence of the change of the forging ratio from 5.9 to 10 was noticed.

Table III shows the results of the investigation of spring steel from 2 melts with different content of large inclusions ($d \geq 30$ mk). The total content of inclusions in the two investigated materials C_1 and C_2 was similar but the content of large inclusions was much greater in the case of bar C_2. This difference influenced the value of the reduction of area, elongation and fracture stress of transverse specimens cut out from bars C_1 and C_2. The anisotropy ratio of reduction of area was greater than 0.4 for better steel and much smaller than 0.4 for worse steel (in case of tensile strength R_m=150 kg/mm^2).

Table IV shown the results of the investigation of a Cr-steel (R_m=80 kg/mm^2) with different forging ratio and from different melts (conventional and consumable electrode melted). From this investigation it follows that the properties of transverse specimens and the anisotropy ratio of reduction of area are much higher for the consumable electrode melted steel. This steel did not contain any large incl. and therefore the fatigue limit of transverse specimens was near to the fatigue limit of longitudinal specimens and much higher than for conventional steel.*

3. The influence of inclusions on the creep properties.

Creep tests were carried out (at 500°C) in order to compare the properties of the consumable electrode remeldet steel with the properties of the conventional melt. The results are presented in Fig.2 and 3. The time of 0.2% elongation was much greater for the remeldet steel (Fig.2). The elongation of specimens tested at constant load σ=14 and σ=23 kg/mm^2 in the time of 1000h was smaller for the cleaner steel. (Fig.3). The difference between the elongation of the two kinds of steel was greater at σ=23 kg/mm^2. The rupture time at σ=28 kg/mm^2 was two times greater for the cleaner steel (65.5 h and 29.5 h correspondly) and the rupture elongation was 5% for this steel and only 2% for the conventional steel.

4. The influence of inclusions on the fatigue properties.

Special fatigue tests were carried out by the author in order to investigate the influence of nonmetallic inolusions on fatigue strength by reversed and fluctuating direct stress of longitudinal and transverse, smooth and notched specimens. The specimens were cut out from billet (A_1 and A_2) and bars (B_1 and B_2) of CrNiMo-steel the mechanical properties of which were shown in Table I. The results of fatigue tests are presented in Table V.

As seen from Table V a higher degree of impurity has a negative influence on the fatigue limit of smooth and notched, transverse and longitudinal specimens in case of both alternating and fluctuating stresses. However, the negative influence of the impurity is smaller than that of the notch, even when the theoretical notch factor is relatively small (K_t=1.73).

The influence of the steel impurity was greater for the alternating than for the fluctuating stress. This may be explained by considering the analogy between nonmetallic inclusions and geometrical notches both acting as stress raisers. Investigations (3) show that the negative effect of a geometrical notch is greater for alternating stress (σ_m=0) than for fluctuating stress (σ_m>0). Similarly the inclusions which are internal stress raisers diminish the fatigue limit more when the mean stress σ_m=0.

From the investigations of Dieter, Ransom and Macleary (1) of steel SAE 4340 it follows that the anisotropy of the fatigue limit

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* The total content of inclusions in conventional and consumable electrode melted steel did not differ much (0.051% and 0.031% for bars sq. 90mm.)

depends on the forging ratio. The results are presented in Table VI. It is evident that the increase of the forging ratio of conventional steel increases the fatigue limit of the longitudinal and decreases the fatigue limit of the transverse specimens. In case of vacuum steel the change of forging ratio from 3.5 to 9 does not effect the fatigue properties.

The anisotropy of the fatigue strength is also connected with the tensile strength of the material (4). Frith (5) investigated specimens with different tensile strengths equal to 95,120 and 175 kg/mm^2. The investigations indicated that the fatigue limit of specimens with tensile strength R_m=175 kg/mm^2 was greater than that of specimens with R_m=120 kg/mm^2 only in the longitudinal direction. The transverse fatigue strength was equal for specimens with greater and smaller tensile strength.

As it results from our investigations of various steels the content of great inclusions (e.g.$d \geq 30$ mk) is more important for steel quality than the total inclusion content. Large inclusions have a negative effect on the fatigue limit as well as on the reduction of area of transverse specimens (see Table I, III and IV). It may be assumed that there is a critical inclusion size below which fatigue limit is not reduced (7,8,9). That idea results also from the observation by Cummings, Stulen and Schulte (7,8) of the size of inclusions found in the fatigue fracture nucleations. These were in general spherical silicates of a size greater than 25 mk. The fatigue life of the specimens statisticaly depended on the size of these inclusions.

Our microscopic investigations of CrNiMo-steel with tensile strength R_m=135 kg/mm^2 show the lack of influence of small inclusions ($d \leq 10$ mk) on fatigue properties. The longitudinal inclusion lines detected by magnetic-particle indication method had no harmful effect on the fatigue life of specimens (10,13). The fatigue life of specimens with fatigue cracks in the area of inclusion stringers was not smaller than for other specimens, Fig.4. The electron micrographs of small spherical inclusions in fatigue tested specimens did not show any distortions resulting from fatigue or from hot working. (Fig.5).

The diminishing of fatigue properties depends not only on the size of inclusions but also on their type. It follows from several investigations (1,5,7,11) that the brittle inclusions (silicates, oxides etc.) are more harmful for the fatigue properties than the plastic sulfides.

Frith (5) investigated the fatigue properties of steel obtained from basic electric furnace and of similar steel made by open-hearth practice. The investigation showed lower properties in the first case. This result was interpreted as due to the presence of spherical silicates and hard angular alumino-silicates in the electric furnace steel. The decrease of the fatigue limit (by rotating bending) of these steels was about 17%. The same value of maximum decrease of the fatigue strength was found in our investigation of steel CrNiMo with Al_2O_3-inclusions (Table V) and by comparing the longitudinal fatigue limit for various melts of steels 30HGSA, 12G2A and 40HNMA with the same tensile strength for every steel mark (2).

Dieter, Macleary and Ranson (1) investigated the influence of the deoxidation practice. Statistical analysis showed that the fatigue limit of the aluminium deoxidized steel was significantly lower than that of the silicon-deoxidized steel (Table VII).

Watanabe (11) investigated two melts with different sulfide inclusion content. The great sulfide content of one melt did not affect the fatigue limit of transverse and longitudinal specimens (with tensile strength R_m=70÷80 kg/mm^2), but decreased the value of the transverse reduction of area (Table VII).

In general, however, the steel with lower plasticity properties of transverse specimens have lower fatigue properties, as seen from Table VII, where results from various investigations are collected. Probably steels with different sulfide inclusion content constitute an exception because plastic inclusions do not produce cavities and cracks affecting the fatigue properties. The elongation of the plastic sulfides in the direction of the forging causes therefore only the anisotropy properties.

As seen from the investigation results the assumption that the fatigue properties are lower in case of lower properties of transverse tensile specimens is correct when comparing forgings with the same hot-treatment, forging ratio and melt practice (e.g. deoxidation practice). It may be assumed that for melts with different content of inclusions of the same type, the steel with greater content of large nonplastic inclusions must have simultaneously lower fatigue properties and smaller values of reduction of area, elongation and fracture stress of transverse specimens.*

Many facts show the parallel influence of the impurity degree on the fatigue properties and on some tensile properties of transverse specimens. For example, increasing of tensile strength and forging ratio increases the influence of the impurity degree on the fatigue properties and on the results of transverse tensile test.

The investigations of Rudnik and Malkiewicz (14,15) showed that

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* Dieter, Macleary and Ransom (1) point out that fatigue is a more structure-sensitive property than transverse reduction of area. This is undoubtedly right and a high value of transverse reduction of area is not sufficient for a high value of fatigue limit. The dependence of fatigue properties on transverse ductility was first discovered by Ransom and Mehl (12).

during hot working of steel longitudinal cavities, cracks and distortions appeared (Fig.6) as the result of the difference between the deformability of plastic steel and brittle inclusions. These defects are greater for nondeformable large inclusions. The longitudinal orientation of these microdefects together with that of residual tension stresses in the matrix adjacent to these inclusions explains the anisotropy of fatigue strength.

Similar reasons effect the anisotropy of plasticity, except for the residual stresses which disappear after the yield limit is exceeded. The cavities connected with brittle inclusions and the elongated plastic inclusions decrease the plasticity of transverse specimens similar to the influence of a transverse geometrical notch.

The increase of the forging ratio decreases the fatigue limit and the reduction of area of transverse specimens and increases these properties for the longitudinal specimens. The decrease of transverse properties is connected with extension of microdefects in the forging direction. Forging also crushes and diminishes the inclusions. Due to this an increase of longitudinal fatigue strength of hot worked steel may occur.

The effect of the brittle inclusions size and of the forging ratio on the size of the microdefects explains the dependence of fatigue limit and reduction of area of transverse specimens on the above mentioned factors.

6. Conclusions

1. The reduction of area, elongation and fracture stress of transverse tensile specimens is influenced by the content of large nonmetallic inclusions.
2. The fatigue limit of transverse and longitudinal, smooth and notched specimens is influenced by the content of large brittle inclusions.
3. In case of steel with the same heat treatment, forging ratio and inclusion type the steel with smaller transverse ductility and fracture stress contains more large nonmetallic inclusions and has in general worse fatigue properties.
4. There is a critical size of inclusions below which fatigue limit of steel (with a given tensile strength) is not reduced.
5. The increase of the forging ratio decreases the fatigue limit of transverse specimens and increases the fatigue limit of longitudinal specimens in case of conventional melted steel but does not effect the fatigue properties of consumable electrode melted steel (because it contains only small inclusions).
6. The effect of inclusions on fatigue limit is greater in case of alternating than fluctuating stresses.

7. The harmful effect of inclusions on the fatigue limit and fracture stress of conventional melted steel is in general less than 20%. The influence on the transverse ductility may be much greater.
8. The time of 0.2% creep elongation is much greater for the consumable electrode melted steel than for the conventional melted steel.

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Table I

Comparison of mechanical properties of CrNiMo-steel $/R_m = 135$ kg/mm^2/ of different purity.

Mate-rial	Forging ratio	Rel.area of inclusions		Transverse properties				Anisotropy ratio of Z
		d≥5mk %	d≥30mk %	Reduction of area Z%	Elongation A_5%	Impact Str. $\frac{kgm}{cm^2}$	Fatigue limit $\frac{kg}{mm^2}$	
A_1 sq140	8.5:1	0.094	0.0036	34.2	9.6	2.7	44	0.69
A_2 sq140	8.5:1	0.297	0.1302	10.5	4.5	2.5	40	0.21
B_1 d.70	43 :1	0.054	0.0045	28.6	9.0	2.8	43	0.60
B_2 sq65	22 :1	0.124	0.0626	16.5	8.1	2.5	40	0.34

Table III

Comparison of mechanical properties of CrNiMoV-steel $/R_m$=150-160 kg/mm^2/ of different purity

Mate-rial	Rel.area of inclusions		Transverse properties				Anisotropy ratio of Z
	d≥5mk %	d≥30mk %	Elongation A_5%	Fracture stress R_u kg/mm^2	Impact strength kgm/cm^2	Reduction of area Z%	
C_1	0.0495	0.0019	5.6	185	1.6	18.9	0.42
C_2	0.0575	0.0185	4.4	169	1.7	12.1	0.27

Table II

Synopsis of anisotropy ratios of mechanical properties of 19 melts and results of their metallogrphical examination. CrNiMo-steel,tensile strength R_m=110 kg/mm^2.

Forging ratio	Anisotropy ratio for mechanical properties /average for 3-4 spec./				Classification of inclusions ac. Pol.Stand. /average for 8 specimens /							Degree of impurity
	Reduction of area	Elongation	Fracture stress	Impact str.	Stringers of oxides	Brittle silicates	Ductile silicates	Max. for 1, 2 or 3	Grains of oxides	Nondef. grains of silicat.	Sulphides	
					1	2	3	4	5	6	7	
10 : 1	0,85	0,64	0,90	0,72	0,5	0,6	0,9	0,9	0,9	0,9	0,9	greater
	0,87	0,84	0,86	0,67	0,6	0,75	0,5	0,9	0,7	0,6	0,75	
	0,44	0,74	0,62	0,57	1,8	1,75	0,8	2,25	0,8	1,8	0,7	
	0,70	0,75	0,75	0,88	0,4	0,4	0,5	0,9	0,5	1,9	0,6	
	0,64	0,74	0,78	0,56	0,9	0,6	0,3	0,9	0,9	2,0	1,1	
	0,75	0,77	0,79	0,66	0,8	0,9	0,75	1,1	0,7	1,5	1,3	
	0,76	0,84	0,87	0,59	0,7	0,4	0,8	1,4	0,1	1,9	0,9	
8,5 : 1	0,87	0,91	0,94	0,80	0,75	1,25	1,2	1,6	0,1	1,2	0,4	greater
	0,81	0,80	0,91	0,69	0,9	1,1	1,1	1,4	0,75	1,75	1,0	
	0,80	0,91	0,87	0,61	0,75	0,3	0,4	0,9	0,25	1,4	0,9	
	0,72	0,86	0,89	0,63	0,5	0,8	0,6	0,9	0,5	1,8	0,9	
	0,38	0,69	0,55	0,47	2,1	2,7	2,0	2,7	1,1	1,4	1,3	
	0,74	0,84	0,83	0,49	1,4	1,0	1,4	1,6	1,0	2,0	1,4	
	0,61	0,78	0,79	0,40	0,7	1,3	1,0	1,62	0,4	2,6	2,25	
	0,80	0,83	0,80	0,56	0,6	0,9	0,2	1,1	0,6	2,3	1,9	
	0,81	0,90	0,80	0,61	0,75	1,1	1,1	1,3	0,4	1,2	0,7	
	0,79	0,89	0,82	0,61	1,1	1,25	1,1	1,6	2,5	2,4	2,0	
8,3 : 1	0,77	0,92	0,86	0,62	0,8	0,7	0,4	1,1	0,4	1,7	1,4	
5,9 : 1	0,81	0,90	0,89	0,60	0,9	1,2	1,0	1,3	0,9	1,3	1,4	

Table IV

Influence of inclusions on mechanical properties of Cr-steel /R_m=80 kg/mm^2/

Kind of steel	Kind of bar and forging ratio	Rel.area of inclusions % d≥30	Anisotropy ratio of Z	Trans. properties			Fatigue li	
				Red.of area Z%	Elongation A_5%	Fracture stress	Trans kg/mm^2	Long. kg/mm^2
Consumable electrode	sq56, 6.4:1	0.0000	0.895	62	19.1	146	38	39
	sq90, 2.5:1	0.0000	0.910	63	19.7	145	38	39
Conventional	sq60, 22:1	0.0086	0.390	26	9.1	99	23	39
	sq90, 9.6:1	0.0034	0.615	39	14.6	109	24	38

Table VI

Influence of forging ratio on fatigue limit /fluctuating bending/ of SAE 4340-steel /1/.

Kind of steel	Forging ratio	Fatigue limit kg/mm^2	
		Longitudinal	Transverse
Conventional	3.5:1	78.5	54.5
	6:1	82	52.3
	10:1	90	47
	50:1	--	44.5
Vacuum	3.5:1	97	84
	9:1	97	84

Table V

Influence of degree of impurity of CrNiMo-steel /R_m=135 kg/mm^2/ on fatigue limit of smooth / ø4 / and notched /r=0.75, K_t=1.73/ specimens /2/.

Material	Degree of impurity	Kind of specimen	Reversed stress		Fluctuating stress	
			kg/mm^2	%	kg/mm^2	%
A_1	small	long. smooth	57	100	76	100
		trans. smooth	44	100	59	100
A_2	great	long. smooth	47	83	70	92
		trans. smooth	40	91	55	93
A_1	small	long.notched	32	100	60	100
		trans.notched	30	100	57	100
A_2	great	long.notched	28	88	59	98
		trans.notched	25	83	54	95
B_1	small	long. smooth	50.5	100	84	100
		trans. smooth	43	100	62	100
B_2	greater	long. smooth	48.5	97	84	100
		trans. smooth	40	93	62	100
B_1	small	long.notched	28	100	62	100
		trans.notched	24	100	56	100
B_2	greater	long.notched	26.5	95	57.5	93
		trans.notched	23	96	48	87

Table VII

Comparison of transverse reduction of area Z_T and fatigue properties of conventional melted steels with similar tensile strength R_m.

No	Kind of material	Kind of melt	Forging ratio	R_m kg/mm^2	Z_T %	Fatigue limit kg/mm^2		Kind of test	Source
						Transverse	Longitud.		
1	4340 8 in. bar " 6 in. bar	Si deoxidized	3,5 : 1 3,5 : 1	117 123	34,4 18,8	75,5 63,5	108 107	rep. bend.	/1/ Ransom
2	4340 8 in. bar " 6 in. bar	Al deoxidized	3,5 : 1 3,5 : 1	124 120	37,1 35,4	58 50	96 89,5	rep. bend.	/1/
3	4340 "	conventional		85,5 87,5	58 23	36,5 32,5	47 43	rot. bend.	/12/ Mehl
4	4340 4 in. bar " 2 in. bar	conventional		125 125	37,3 33,8	48 44	55 52,5	rot. bend.	/1/ Matthews
5	4320 "	with rare earths without " "		123 123		79 72		rep. bend.	/1/
6	NiCrMo rotor shaft "	small sulfides large sulfides	20 : 1 24 : 1	71,6 79,4	29,7 17,5	32,6 32,4	38,5 39,4	rot. bend.	/11/ Watanabe
7	40HNMA surface of billet " core of bil.	small inclus. large inclus.	8,5 : 1 8,5 : 1	138 135	34,2 10,5	44 40	57 47	axial stress	/2/ Buch
8	40HNMA 70mm bar " 65mm bar	small inclus. large inclus.	43 : 1 22 : 1	135 141	28,6 16,5	43 40	50,5 48,5	axial stress	/2/ Buch

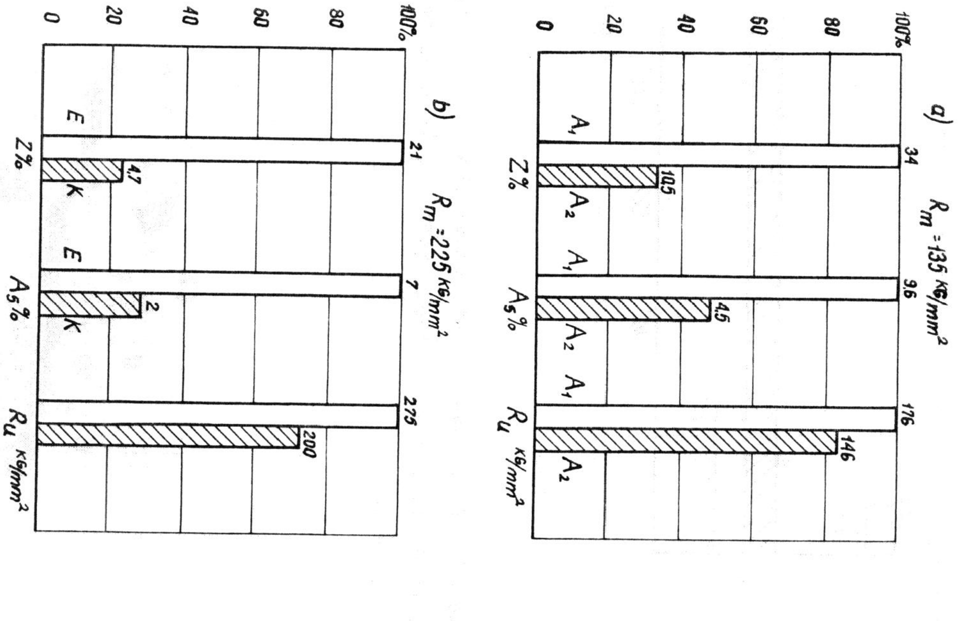

Fig. 1 Comparison of transverse mechanical properties /reduction of area Z, elongation A_5, fracture stress R_u/ of two materials of different impurity degree. CrNiMo-steel 4OHNMA.

a/ Tensile strength R_m=135 kg/mm^2
A_1-surface of the billet, small impurity
A_2-core of the billet, great impurity.

b/ Tensile strength R_m=225 kg/mm^2
E-pure consumable electrode melted steel
K-conventional steel

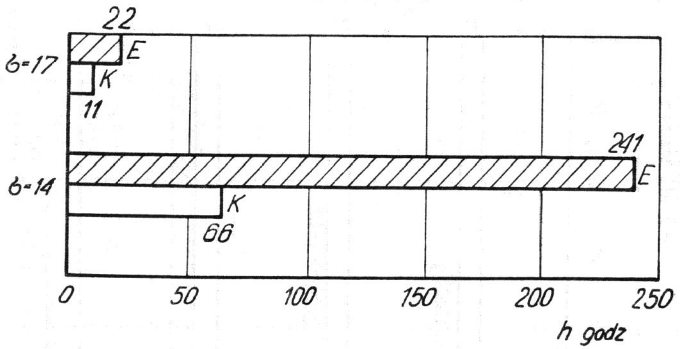

Fig.2 Time of 0.2% elongation of conventional K and consumable E electrode melted 13Cr-steel. t=500°C, $\sigma=14$ kg/mm^2, $\sigma=17$ kg/mm^2 /8 specimens/

Fig.4 Fatigue crack in the area of small nonmetallic inclusions gathering.The fatigue life of the specimen was not smaller than that for other specimens without inclusion stringers. 120X

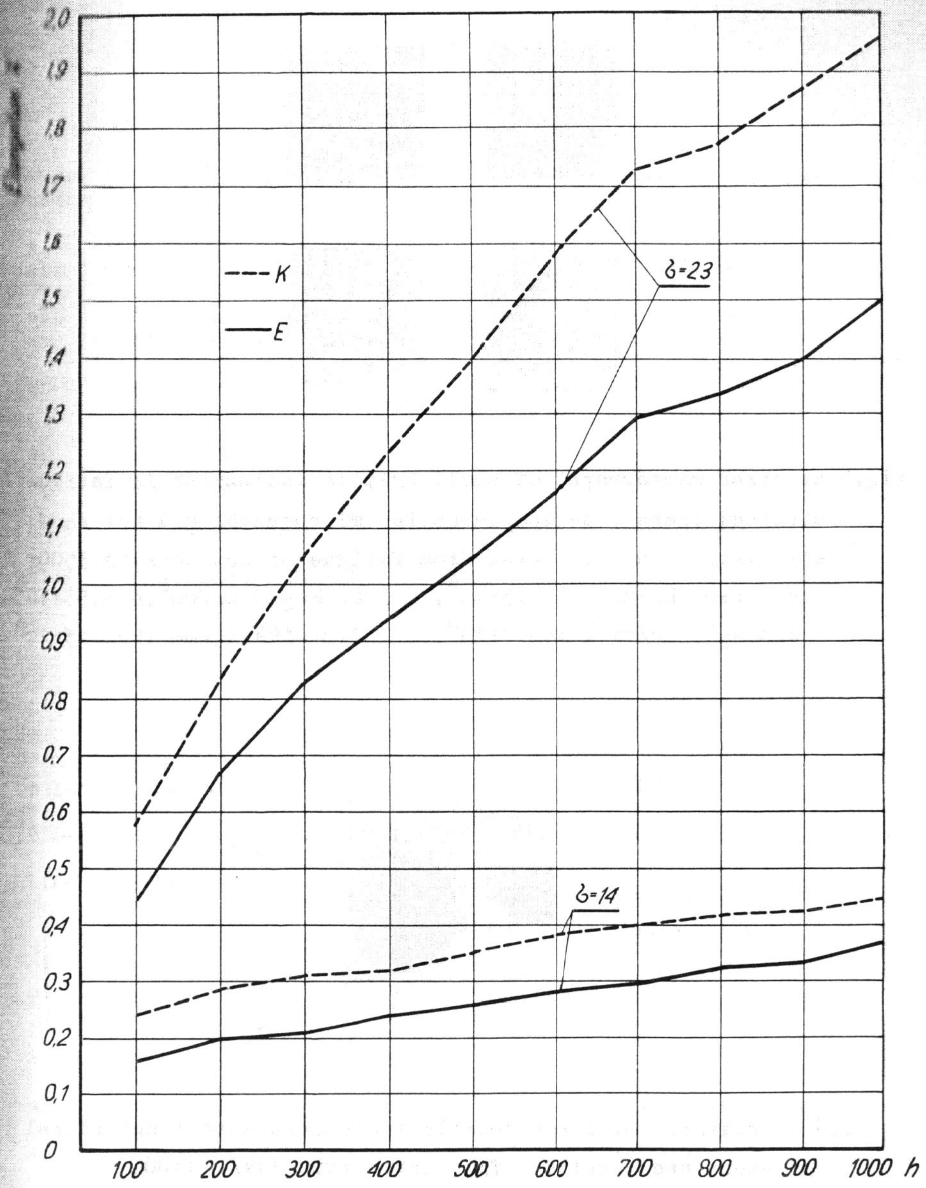

Fig.3 Elongation of conventional K and consumable electrode E melted 13Cr-steel.t=500°C, $\sigma=14$ and $\sigma=23$ kg/mm^2 /6spec./

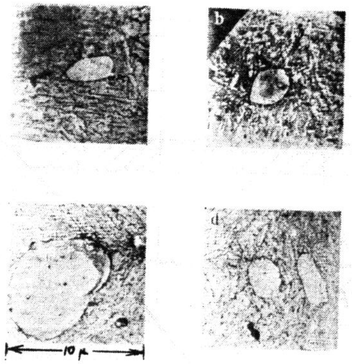

Fig.5 Electron micrographs of small brittle inclusions in fatigue stressed transverse specimens. The micrographs did not show any distortions resulting from fatigue or hot working. 3500x
a. σ =+69 kg/mm^2, N=4.5·10^6, b. σ =±45 kg/mm^2, N=6.55·10^6
c. σ =±44 kg/mm^2, N=3.9·10^6, d. σ =±44 kg/mm^2, N=9.15·10^6

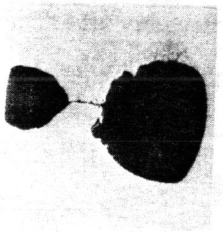

Fig.6 Micrographs of large brittle inclusions with longitudinal distortions resulting from hot working/14/. 1100X

List of Discussors

Lecture Number	Name of Discussors	Lecture Number	Name of Discussors
BI-1	R.F.Landel	BI-9	F.A.McClintock
BI-2	P.Haasen, G.T.Hahn R.M.N.Pelloux	BI-10	A.M.Sullivan
BI-3	N.P.Allen, A.J.McEvily A.M.Sullivan, A.S.Tetelman	BI-12	L.F.Coffin,Jr., J.J.Gilman F.A.McClintock
BI-6	R.R.Hasiguti, D.Hull P.L.Pratt	BI-13	F.A.McClintock
BI-7	F.P.Bullen, D.Hull	BI-15	A.R.Rosenfield
BI-8	J.J.Gilman, P.C.Paris S.Ogawa	BI-16	F.A.McClintock
BII-2	G.T.Hahn	BII-8	S.Takahashi
BII-4	G.T.Hahn, R.M.N.Pelloux	BII-9	N.Ujiiye, ir.C.A.Verbraak A.R.C.Westwood
BII-5	S.Takahashi	BII-10	F.A.McClintock, A.R.Rosenfield
BIII-2	G.T.Hahn	BIII-6	A.R.Rosenfield, V.Weiss
BIII-3	P.L.Pratt N.Ujiiye	BIII-7	H.Furuichi
BIII-4	R.M.N.Pelloux, A.S.Tetelman		