PAPER 36 (SESSION III)

Delayed failure properties of high strength steels in water

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Summary

Delayed failure properties of about 100 heats of high strength steels including maraging steel were investigated. Notched tensile sustained load tests with stress concentration factor 10 were conducted in distilled water.

Strength level of material has close relation to delayed failure sensitivity. Up to about 110 Kg/mm^2 (70 tsi) 0·2% yield strength, all conventional steels tested are insensitive and above which become sensitive to delayed failure almost invariably. As to maraging type steels, this critical yield strength level is estimated 140 Kg/mm^2 (90 tsi).

Increasing test temperature accelerates the phenomenon, and the apparent activation energy is about 13,000 cal/mol.

Insufficient aged or tempered condition both 18 Ni maraging steel and 0·2% carbon low alloy steel are very sensitive to delayed failure in spite of their good ductility.

Influence of each chemical component, and effect of surface decarburization and inhibitors in solution were investigated for the purpose of prevention of failure.

Influence of polarization by means of the contact of other metals and by the potentiostat was studied.

Introduction

Delayed failure, sometimes called delayed fracture, stress corrosion cracking or static fatigue, is a branch of the broad scope of embrittlement caused by environmental attack, that include so called season cracking, hydrogen attack, stress corrosion cracking in stainless steels and so forth.

Nomenclature for each phenomenon is somewhat confused so far. The word 'delayed failure' seems to designate the time dependent failure of high strength steels under static tensile stress in comparatively moderate environment. There are two types in the delayed failure. The one is the fracture definitely caused by excess hydrogen in steel like that encountered in case of flaking or cadmium plated components [1]. The other, in which we are now involved, is the case where appreciable amount of hydrogen is not always detected at least macroscopically.

Present research has begun with the troubles encountered in service of high strength steel bolts for the friction joint and threaded bars for the prestressed concrete, and now gives a general survey of the delayed failure properties in water over many grades of conventional constructional steels and several maraging steels.

Experimental procedure

Sustained tensile load tests were conducted in aerated distilled water because of increased sensitivity than in air. For example, those solvents like alcohol and acetone which dissolve water, are also as detrimental as water. On the other hand steels are more stable against delayed failure in benzene and carbon tetrachloride to which water has negligible solubility [12].

This water environment together with severe stress concentration also simulates the actual service condition of most constructional components as the severest case both in civil and mechanical engineering field.

Notched bolt type specimen used was shown in Fig. 1, of which the stress concentration factor k_t=10, determined by photoelastic study with frozen and sliced epoxy resin specimen.

Nominal applied stress versus time to complete fracture curves were obtained by about ten specimens, and the delayed failure strength was estimated in 100 hours. Fig. 2 shows a typical curve by AISI 4340 quenched and tempered at 480°C.

Notch tensile strength (NTS), which was determined by short time tensile test with the same specimen as mentioned above, was usually higher than ultimate tensile strength (UTS). So when material was stable enough against delayed failure, the endurance limit higher than UTS resulted.

Elevated temperature test up to 80°C was also conducted in aerated distilled water.

About 100 heats of low alloy steels investigated cover 0·2 to 0·6% carbon range. Around 140 Kg/mm^2 UTS level, 0·2% C steel tempered at about 250°C generally shows better delayed failure endurance than higher carbon steel tempered at 450 to 550°C on the criterion of the same UTS. Moreover, as described later the critical strength level with regards to the delayed failure resistance or the reliability of high strength steel for constructional component is estimated at 110-120 Kg/mm^2 0·2% yield strength, or identical 130-140 Kg/mm^2 UTS. Therefore the majority of conventional steel investigated were 0·2% C Mn-Cr, Cr-Mo, Ni Cr-Mo and 13% Cr steels with additions of Al, Ti, Zr, V, Nb, Cu, P, S, Pb, N and O, and these were examined mostly at 110 to 150 Kg/mm^2 UTS level. Others were 0·3-0·4% C Si-Mn-Cr, Cr-Mo and Ni-Cr-Mo steel, which were examined over 70 to 200 Kg/mm^2 UTS varied by controlling tempering temperature. 18 Ni (250 ksi, 300 ksi), 20 Ni and Ni-Cr-Co-Mo maraging steel were examined at each specified strength level.

Conventional steels were mostly molten in 100 Kg induction furnace, and maraging steels in 100 Kg vacuum induction furnace.

Surface condition of specimen was as machined for low alloy steels, and as aged condition for maraging steels unless otherwise stated.

Results

(1) *Strength level*

Strength of material has foremost influence on delayed failure properties as shown in Fig. 3 in which one plot represents a series of test with about 10 specimens. It will be said from Fig. 3 that delayed failure strength of all conventional steels can be described simply by one curve. Up to 110 Kg/mm^2 0·2% yield strength it is almost equal to NTS and increases linearly with UTS by a factor of about 1·5 (NTS/UTS). This means that steel is stable or reliable enough as a design engineer always hopes.

But above this critical strength level all conventional steels become sensitive—that is, there is possibility of accidental failure in constructional component, at least in the condition of k_t = 10 and water environment.

It could be also mentioned that the conventional authoritative steel specifications compiled by huge experimental data and previous service experiences, have been appropriate in regard to their reliability or delayed failure resistance now revealed. Because if chemical composition and heat treatment practice, especially tempering temperature, are observed as the specification prescribes, 0·2% yield strength of the constructional steels become mostly below 110 Kg/mm^2, or identical UTS 120 Kg/mm^2.

According to the delayed failure test this critical is clearly and qualitatively given with the maximum stable load bearing capacity. To the contrary by conventional tensile or impact test this situation is only ambiguously pointed out, because reliability estimation in this case depends on the monotonously decreasing stability characteristics with increasing strength like elongation, RA and impact energy.

As to maraging steels this critical strength level will be estimated 140 Kg/mm^2 0·2% yield strength, or identical 150 Kg/mm^2 UTS. This qualitatively shows the superiority of maraging steel over conventional steel. According to Table 1, a tentative reasonable classification of martensitic high strength steel, the conventional low alloy steel and maraging steel correspond to the two extremes. If the other two kinds are investigated, role of intermetallic compound and impurity level in improving steel properties would be estimated respectively, however we must also consider the effect of important elements, Ni, Cr, Mo and Co.

Crack propagation path in low alloy steel was predominantly along former austenite grain boundary with some wavy transgranular branch. In 18 Ni and 20 Ni maraging steel, it was mostly transgranular and sharp straight appearance suggesting dependency to the particular crystallographic plane, probably (100).

Both conventional and maraging steel are actually used over each critical strength level, especially in aircraft components. In order to meet this circumstance, the delayed failure strength must be investigated at lower stress concentration in water as well as in air; and it is expected that the critical strength level will increase. For instance Table 2 shows delayed failure strength at k_t = 6·5, and 4340 and particularly maraging steel are much more stable than shown in Fig. 3 (k_t = 10). It is also seen in Table 2 that at comparable strength level, 180 Kg/mm^2 UTS, the stability of piano wire (5 mm dia.) is better than 4340 and inferior to maraging steel.

(2) *Temperature dependence*

Increasing test temperature from 25°C to 80°C enhances delayed failure shown in Fig. 4. At 80°C the phenomenon is accelerated about 30 times than at 25°C and this indicates that the long time test will be necessary for actual service. It has been also reported that high strength steel bolts in service fail more frequently in summer time.

This result is not explained only by the ductility of material or mobility of dislocations as in case of low temperature embrittlement, and indicates the important role of environmental attack. However the more ductile material in the low temperature brittleness test like Charpy impact test, generally shows the better endurance in the delayed failure test.

The apparent activation energy in water is estimated 13,000 cal/mol as shown in Fig. 5. Attempt to estimate the activation volume, the contribution of applied stress, as well as the net activation energy was unsuccessful, probably because of severe notch acuity and combined process of the initiation and the propagation, except final instantaneous rupture, of the delayed failure crack.

The value 13,000 cal/mol is much higher than reported activation energy for hydrogen diffusion in iron, 2,000 cal/mol, and the binding energy of hydrogen and dislocation, 6,400 cal/mol [2]. Therefore the delayed failure in water as a rate process is not controlled by hydrogen diffusion.

Another experimental evidence concerned with hydrogen is that baking treatment in vacuum at 200°C for 48 hour has no effect on delayed failure characteristics in water [3]. So it is postulated that hydrogen amount of 0·1-0·5 ppm contained in usual forged piece is not main cause in the delayed failure in water.

(3) *Heat treatment*

The tempering temperature and aging temperature also have some effect on delayed failure endurance.

Fig. 6 is a usual tempering characteristics curve of 0·2 C-Mn-Cr steel with special reference to the delayed failure strength and NTS. When tempered around 350°C and below 200°C, the steel has poor resistance. As to tempering at 350°C, it is postulated that there exists close relation to the temper brittleness. As to tempering below 200°C however, it is rather difficult to explain because even as quenched condition those 0·2% C steel have similar strength and enough ductility to that tempered at 250°C.

Fig. 7 shows similar aging characteristics curve of 18 Ni-300 ksi maraging steel. When aged at 440°C it has unexpectedly inferior delayed failure endurance in spite of higher elongation, RA, NTS and lower UTS than aged at 480°C, standard aging temperature.

The common cause for these two cases would be that the precipitation process is premature–that is, the carbide for 0·2% C steel or the intermetallic compound for maraging steel is sub-electron-microscopic size.

(4) **Chemical Composition**

Although the strength level has the foremost influence on delayed failure sensitivity, chemical composition of material has also some influence. The effect of conventional amount of each element is investigated mostly on 0·2% C low alloy steel, and the results are summarized as follows.

Cr, Mo, V, Nb, Ti, Zr and Ni have generally good influence.

Si, Mn, S, Cu and B have no appreciable effect.

P, Pb, O and N are detrimental. C is mostly undesirable. So the carbide and nitride formers together with Nickel improve the delayed failure endurance. These results are approximately consistent with those obtained on the development of high strength steel along a course of estimating ductility only.

One remarkable example is shown in detail in Table 3. Phosphorus is detrimental as anticipated, but sulphur would have rather favourable effect on delayed failure properties only in spite of reduced ductility and NTS, typically shown in case of Mn-Cr steel including 0·081% S, much higher S content than in average commercial steel.

(5) *Decarburization treatment for prevention of failure*

To prevent the delayed failure, surface treatment must be the one to be considered. From Fig. 3 it is reasonably agreed that any treatment to reduce the strength or hardness in surface layer below 120 Kg/mm^2 UTS will be effective.

Table 4 shows the results with softened surface layer specimen by wet hydrogen decarburization. Delayed failure strength is improved expectedly by about 0·4 mm depth decarburization in these three steels, particularly in 4120 steel.

Moreover, a simple austenizing treatment in air at 900°C before quenching, is still effective with about 0·05 mm decarburized layer, always for 0·20% C level, sometimes erratic for 0·30-0·60% C level.

(6) *Plating and contact of other metals*

Electroplating of Cu and vapourized layer of aluminum had no effect to prevent the failure.

The influence of electrical contact in aerated water of other metals which were inserted as washers of 1 mm thick, was investigated. Contact of Mg and Zn washers are detrimental as shown in Fig. 8, and this is interpreted as the hydrogen embrittlement induced by cathodic current on to steel specimen. Macroscopic crack path was altered too. Usually tensile stress axis is normal to crack plane, however with Mg and Zn washers two crack plane appeared each along maximum shear stress plane.

Other metals have no appreciable influence on life and crack path.

(7) *Environmental effect*

City water containing about 20 ppm of Cl^- and other ions, gave the same delayed failure characteristics as distilled water. 0·3% NaCl solution, corresponding Cl^- amount 1800 ppm, accelerated delayed failure about 30 times faster than distilled water on 125 Kg/mm^2 UTS 4120; and 3% NaCl solution, 100 times.

The effect of corrosion inhibitors were investigated. Among them vapour phase inhibitor (VPI, Dicyclohexylammonium Nitrite) was very effective to prevent the delayed failure when added 0·3% in distilled water, supposedly because of adsorption of VPI on steel surface. Delayed failure strength in 100 hours of 0·2% C alloy low steel of 150 Kg/mm^2 UTS and 225 Kg/mm^2 NTS, increased from 100 Kg/mm^2 to 200 Kg/mm^2 by addition of 0·3% VPI. In this case the means to prevent corrosion is also effective to prevent the delayed failure.

It will be concluded that the means to prevent the contact between material and water is the desirable one for this purpose. For example, the adhesives or ordinary painting is still effective at least for short periods.

(8) *Delayed failure test under polarization*

Impressed current technique by the potentiostat was applied to examine which mechanism is operating, stress corrosion cracking or hydrogen embrittlement. It is impossible to use distilled water as media in potentiostatic study because of its poor electrical conductivity. 0·3% NaCl solution will be one of proper choice of media moderately corrosive, but with some electrical conductivity.

Fig. 9 shows that under constant applied stress anodic polarization of specimen gives shorter life and cathodic polarization gives longer life around natural potential, though too much cathodic polarization affect adversely. This result corresponds to that obtained by Hughes *et al.* with 3% NaCl solution [4, 5].

In 0·3% NaCl solution the predominant mechanism is considered the stress corrosion cracking in which anodic dissolution plays the leading role. It might be suggested that in distilled water still the stress corrosion mechanism operates.

Polarization study was also conducted in pH 5 buffer solution (0·1 mol citric acid and 0·2 mol NaOH/l), and impressed current did not affect the life. There was no peak like that shown at –0·75V in Fig. 9. Therefore it is not clear which mechanism operates in this buffer solution.

(9) *Penetration of hydrogen isotope into steel*

It has long been recognized that hydrogen penetrates into steel during immersion in acid solution and amount of absorbed hydrogen can be analyzed by ordinary gas analysis method [6]. It is also well known that hydrogen amount enough to be analyzed, namely above 1 ppm, cause hydrogen embrittlement like in the flaking in ingot and the delayed failure in cooperation with applied stress [1].

However in water, whether hydrogen penetrates into steel or not, and whether it embrittles material even if it penetrates, is uncertain because of difficulty in hydrogen analysis of small amount within any particular area.

Grunberg *et al.* made the experiment with hydrogen isotope, tritium, on hydrogen penetration into hard bearing ball in relation to pitting life during service [7]. According to their result, the depth of penetration was 1 μ, and it was concluded by them that the acceleration of pitting failure of steel balls by water contamination in mineral oil lubricants could be explained by hydrogen embrittlement.

Present experiment was performed with tiny sheet bend specimen of quenched-tempered 4120 by soaking 20 hours in tritiated water, 1 curie/15 cc. After rinsed in water, alcohol and acetone, radioactivity was observed by the gas flow counter which is capable of detecting weak beta ray from tritium.

Table 5 shows that more tritium was absorbed when bending moment was applied, than without load. After polishing by emery paper the activity still existed, though removal amount was not certain.

Assuming that non active hydrogen is also absorbed proportionately and the depth of penetration is 1 μ and together with the fact that half life is 12·3 years and 1 curie produces $3{\cdot}7 \times 10^{10}$ disintegration per second, total hydrogen amount in surface layer is estimated 1 to 5 ppm. This would mean that hydrogen embrittlement mechanism cannot be neglected in case of the delayed failure of high strength steel in water.

Discussion

There are three mechanisms to explain delayed failure phenomenon—they are: (A) stress corrosion cracking, (B) embrittlement by excess hydrogen and (C) embrittlement by hydrogen adsorption on steel surface.

According to the results of our test under polarized condition, it will be concluded that the stress corrosion cracking mechanism is predominant in dilute 0·3% NaCl solution.

However it was observed that hydrogen was absorbed within the surface layer of specimen by study with tritium. Another evidence about hydrogen embrittlement in neutral solution is that 180 Kg/mm^2 UTS 4340 hollow specimen surrounded by boiling 3·5% NaCl solution failed under the applied tensile stress by the crack originated within the wall not at the specimen surface [8]. Hydrogen evolution was also detected in the interior prior to failure. In this case the precipitated hydrogen gas pressure concept [9] seems to be applicable.

Troiano *et al.* reported the discontinuous crack growth of 155 Kg/mm^2 UTS 300M steel specimen in distilled water. The discontinuous growth together with the reversibility of incubation period upon reloading would suggest the hydrogen embrittlement mechanism [10]. They proposed the hydrogen cracking theories which consider that the hydrogen which is absorbed into the lattice is the embrittling agent.

The third concept is based on the decrement of surface energy by the adsorption of hydrogen atom on the steel surface. Hancock and Johnson [11] reported that hydrogen gas and water vapour at atmospheric pressure caused crack growth without incubation period for initiation in 160 Kg/mm^2 yield strength steel.

As to the present case, the mechanism is still not clear, because the stress corrosion crack tendency and hydrogen embrittlement mechanism must coexist at least in NaCl solution, and it seems contradictory from a standpoint of the polarization experiment.

Besides we must have attention on the strength level of material which has close relation to all these three mechanisms, especially when we consider the prevention of failure.

Conclusion

(1) Delayed failure properties of high strength steel firstly has a close relation with the strength level of material. All conventional low alloy steels tested with $k_t = 10$, become sensitive to delayed failure in water above 110 Kg/mm^2 yield strength or identical 120 Kg/mm^2 UTS. This fact seems to correspond to the general concept about the unreliability of high strength steels in the past and describes it clearly and qualitatively.

Beside the predominant influence of strength level, secondarily the chemical composition of material more or less affects the delayed failure endurance. Generally carbide and nitride forming elements have favourable effect, but gas element, phosphorus and lead are detrimental.

Thirdly improper heat treatment like premature aging of 18 Ni maraging steel cause an unanticipated drastic decrement in delayed failure endurance, even if it shows good ductility in terms of RA, Charpy impact energy, etc. Temper brittleness observed around 350°C tempering in 0·2% C low alloy steel also causes another decrement.

(2) Delayed failure is enhanced by increasing test temperature; therefore not only the ductility or dislocation mobility in the material, but also the reaction between material and environment must be considered.

The impressed current study in 0·3% NaCl solution showed stress corrosion cracking tendency in which anodic dissolution prevails, but the tritium absorption experiment contradictory suggested the hydrogen embrittlement mechanism. Hydrogen adsorption on the surface will be another effect which must be considered.

(3) Prevention of the delayed failure has two categories.

One is the way to decrease the strength of surface layer of the component. For example decarburized surface layer about 0·4 mm depth gave a good result.

The other is the way to prevent the contact between water and steel by any surface treatment or by environmental control. Detrimental effect of Mg and Zn washers suggests that plating of Mg and Zn or the cathodic protection method would be erratic, and rather simple covering like painting will be useful. Vapour phase Inhibitor dissolved in water which is believed to be adsorped to steel surface, has remarkable effect to prevent failure. It is intensified that the prevention of delayed failure is not always identical with the prevention of corrosion.

Another way to improve the delayed failure properties must be the consideration of chemical composition, though difficulties are anticipated so far as conventional impurity level is maintained. High alloy steel with low impurity level like maraging steel is promising.

References

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Table 1
Classification of high-strength steel

IMPURITY LEVEL / HARDENING MECHANISM	CONVENTIONAL LEVEL	P, S < 0.010 % Si, Mn < 0.10 % (MOSTLY MOLTEN IN VAC.)
SOLID SOLUTION HARDENING BY C & PRECIPITATION OF CARBIDE	CONVENTIONAL QUENCHED AND TEMPERED STEEL: AISI 4120, 4340, H11 etc.	DENOTATION NOT GIVEN: HP-9-4 (Republic Steel Co., U.S.A) etc.
PRECIPITATION OF INTERMETALLIC COMPOUND	PRECIPTATION HARDENING STAINLESS STEEL: 17-7 PH, PH15-7Mo 17-4 PH etc.	MARAGING STEEL: 18Ni, AM 367 etc.

ALL KINDS ARE HARDENED MORE OR LESS BY MARTENSITE CONFIGURATION

Table 2
Comparison of delayed failure endurance in different types of steel at 180 Kg mm² U T S level

TYPE OF STEEL	HEAT TREATMENT	0.2 % YIELD STRENGTH Kg/mm²	UTS Kg/mm²	RA (%)	NTS Kg/mm² *	100HR DELAYED FAILURE STRENGTH IN WATER Kg/mm² *
AISI 4340	850°C QUENCHED 320°C TEMPERED	152	176	49	240	90
PIANO WIRE	COLD DRAWN TEMPERED	140	172	41	230	205
MARAGING 18Ni 250	815°C ANNEALED 490°C AGED	178	184	57	290	260
MARAGING 18Ni 300	〃	193	198	56	300	250

* STRESS CONCENTRATION FACTOR Kt ≃ 6.5
DIA. 5mm, NOTCH DIA. 3 mm, NOTCH RADIUS 0.03mm

Table 3
Effect of phosphorous and sulphur on delayed failure properties

SPEC.	CHEMICAL COMPOSITION C	Si	Mn	P	S	Cr	Mo	HEAT TREAT-MENT	0.2 % YIELD STRENGTH Kg/mm²	UTS Kg/mm²	RA (%)	NTS Kg/mm² *	100Hr DELAYED FAILURE STRENGTH IN WATER Kg/mm² *
4120	.18	.15	.82	.013	.010	1.02	.34	900°CWQ 250°CAC	115	138	59	200	150
〃 (S)	.18	.12	.79	.013	.026	1.02	.34	〃	111	134	56	173	160
〃 (P)	.18	.15	.83	.036	.010	1.00	.35	〃	115	138	60	182	105
〃 (P, S)	.18	.14	.80	.036	.027	1.00	.35	〃	114	137	59	181	125
Mn Cr	.18	.23	1.32	.011	.014	1.50	—	900°CWQ 200°CAC	118	143	57	200	110
〃 (S)	.18	.22	1.30	.011	.081	1.50	—	〃	124	137	48	161	120

* SPECIMEN SHOWN FIG. 1, Kt ≃ 10

Table 4
Effect of decarburization on delayed failure properties

SPEC.	HEAT TREAT-MENT	MECHANICAL PROPERTIES 0.2% YIELD STRENGTH Kg/mm²	UTS Kg/mm²	ELONG-ATION (%)	RA (%)	SURFACE CONDITION	HARDNESS (VICKERS) DISTRIBUTION SURFACE ** (Hv)	CENTER (Hv)	NTS Kg/mm² *	100HR DELAYED FAILURE STRENGTH IN WATER Kg/mm² *
AISI 4340	850°C OQ 320°C AC	—	182	13	46	AS MACHINED	530	530	156	80
		164	182	14	49	DECARBURIZED	400	530	205	140
AISI 4140	850°C OQ 400°C AC	147	164	14	48	AS MACHINED	480	480	129	70
		151	164	15	49	DECARBURIZED	130	480	247	110
AISI 4120	900°CWQ 250°CAC	127	151	16	6[illegible]	AS MACHINED	450	450	223	180
		130	150	17	62	DECARBURIZED	160	450	241	230

* SPECIMEN SHOWN IN FIG. 1
** 0.05 mm DEEP FROM SURFACE,
MICRO-VICKERS HARDNESS (LOAD, 200 gr)

Table 5
Tritium penetration into steel surface

MATE-RIAL	UTS Kg/mm²	APPLIED STRESS Kg/mm² *	SOAKING TIME (Hr) **	COUNTING RATES BY GAS FLOW COUNTER (Q GAS) *** CONDITION	COUNTS/MIN ****
AISI 4120	140 250°C TEMPERED	about 120	20	RINSED	1050 ± 15
				RINSED AND POLISHED	190 ± 3
				〃 AGAIN	125 ± 5
		0	20	RINSED	259 ± 5

* SPECIMEN, 0.17X4.0X11.75 mm; TWO POINT LOADING DISTANCE, 10.6 mm
** IN TRITIUM WATER, 1 CURIE/15CC
*** Q GAS, He + 1% ISOBUTANE
**** BACK GROUND, 10 COUNTS/MIN

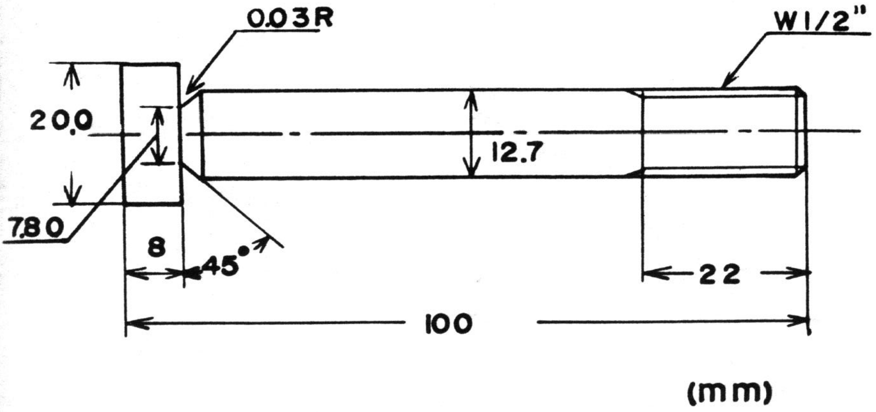
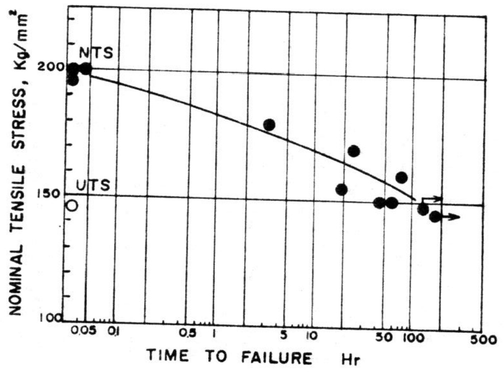


Fig. 1. Specimen for delayed failure test, stress concentration factor *Kt* ≃10.



AISI 4340, 850°C QUENCHED
480°C TEMPERED

0.2% YIELD STRENGTH	134 Kg/mm²
ULTIMATE TENSILE STRENGTH	146 Kg/mm²
ELONGATION	12 %
REDUCTION OF AREA	43 %
NOTCH TENSILE STRENGTH	199 Kg/mm²
DELAYED FAILURE STRENGTH IN 100 HOURS	147 Kg/mm²

Fig. 2. Typical delayed failure curve.

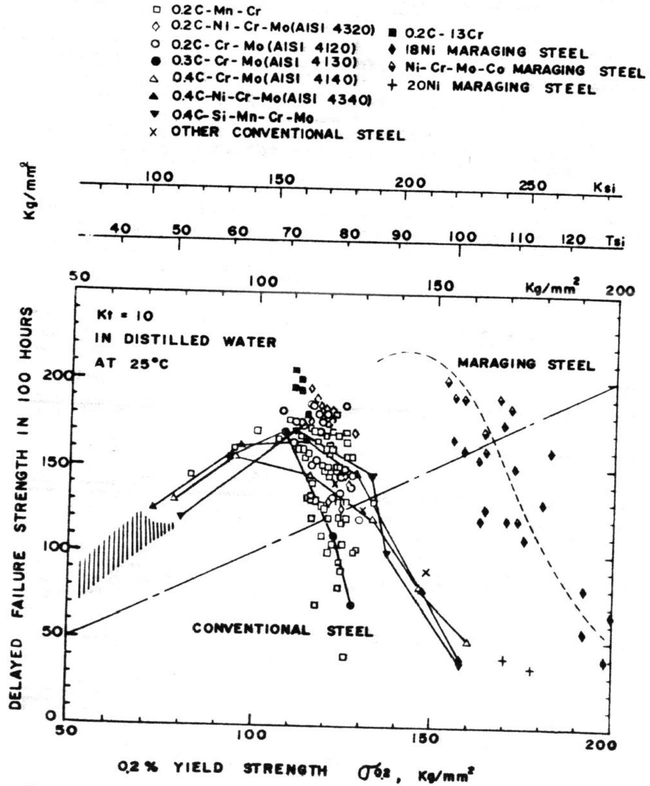
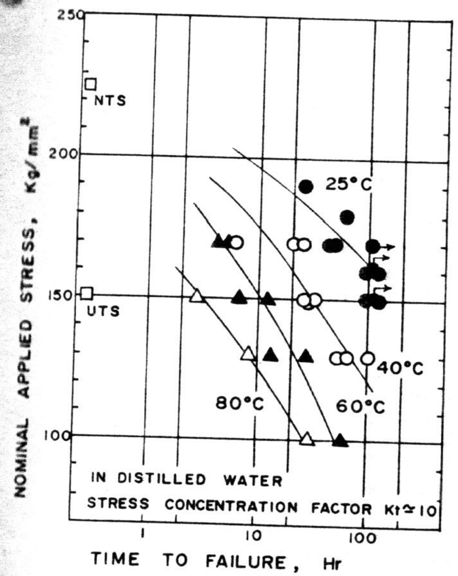


Fig. 3. Delayed failure endurance vs. 0·2% yield strength.



0.2C-1.2Mn-2.2Cr-0.1Ti
900°C QUENCHED
250°C TEMPERED

0.2% YIELD STRENGTH	125 Kg/mm²
UTS	151 Kg/mm²
RA	57 %
NTS	225 Kg/mm²

Fig. 4. Temperature dependence of delayed failure.

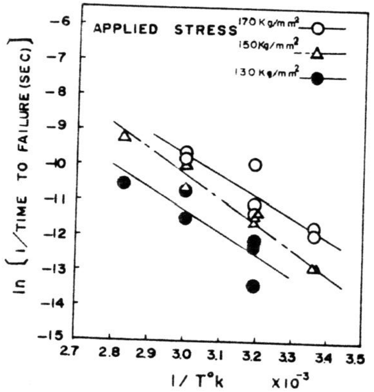


Fig. 5. Apparent activation energy (data from Fig. 4).

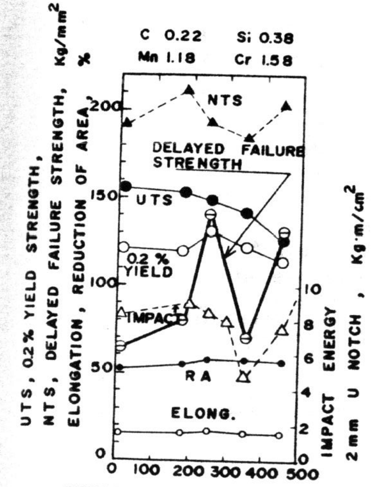


Fig. 6. Tempering temperature vs. mechanical and delayed failure properties in 0·2% C·Mn·Cr steel.

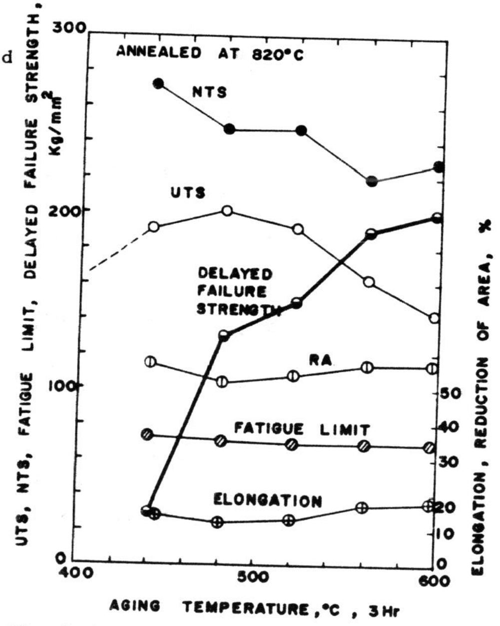


Fig. 7. Aging temperature vs. mechanical and delayed failure properties in 18Ni 300 Ksi maraging steel.

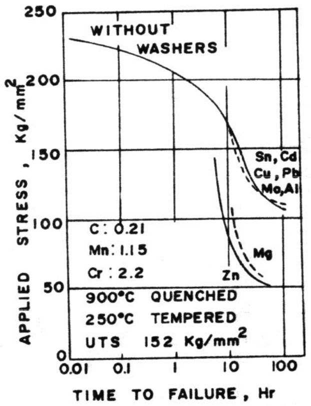


Fig. 8. Effect of contact of other pure metals on delayed failure in 0·2% C·Mn·Cr steel in distilled water, at 25 C.

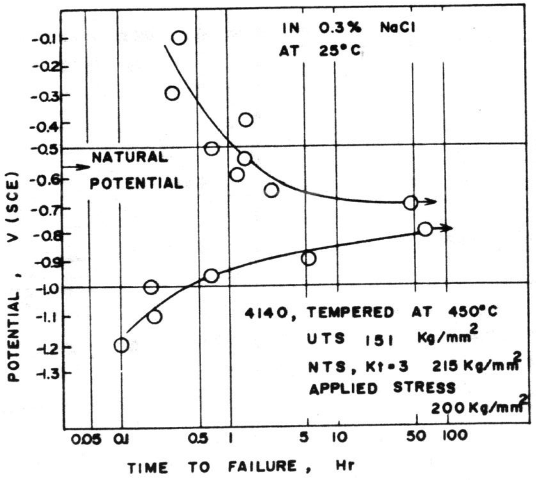


Fig. 9. Delayed failure test under polarized condition.