HEAT TREATMENT OF CREEP RESISTANT STEELS

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INTRODUCTION

Before discussing the heat treatment of creep resistant steels, a few words about creep will be in order. When a metal is subjected to a stress for long time at an elevated temperatures, it undergoes plastic deformation; this time dependent accumulation of strain is known as creep. Creep limits the life time of components. Fig. 1 shows the creep phenomenon as well as some other terminologies associated with creep.

Creep strength is obviously a function of time, temperature and stress. There is also another variable which needs to be considered is the internal structure of the metal or alloys. The internal structure will include factors such as density and arrangement of dislocation in metals which will vary according to the matrix: martensitic, bainitic and ferritic; size and distribution of precipitate particles; the concentration of alloying elements in solid solution; and grain size. Unfortunately, these structural variables depend in a complicated manner on the previous plastic deformation and heat treatment history of the metals and alloys. Hence, it is not always possible to control these factors. Also, of all the variables that controls the rate of plastic deformation, internal structure is the most difficult to evaluate.

The creep resistant steels for various applications like tubing, boiler drum, main steam pipe, rotors and turbine blades, castings etc. can be put in three categories based on the microstructure: ferritic, bainitic and martensitic. Table 1 and Table 2 shows the composition of the ferritic steels. It also shows the end use and corresponding specifications. Table 3 gives the composition and specification of martensitic (12% Cr type) for turbine blading in application as well as austenitic steel for superheater tubing. As can be seen all the steels contain in common Cr, Mo with and without V. Cr usually provides the oxidation resistance whereas Mo and V give rise to precipitation hardening and solid solution hardening. In general commercial heat resistant alloys are based on a matrix which has a solid solution. However, this is further strengthened by precipitation hardening. Since creep resistant steels are subjected to high temperature exposure for an extended duration of 20 - 30 years precipitates are subjected to softening process (over aging). Heating of the alloy for a prolong period can also cause resolution of precipitates. An interesting aspect of certain creep resistant alloys is that the original precipitates may go back into solution while a second precipitate forms.

High strength creep resistant alloys sometime can have limited ductility because of greater improvement in strength of the grain than in the strength of the grain boundaries. For instance, formation of precipitate free zone near the grain boundary is susceptible to give rise to poor ductility.

The heat treatment to be given to a steel obviously depends on the several factors :

- Property requirements:
  - — short-term e.g., impact, tensile etc.
  - — long-term e.g., creep
- Operations during fabrication e.g., welding and bending

HEAT TREATMENT OF TUBING AND PIPING

Generally low alloy steels containing Cr and Mo and in some cases V are used for tubing and piping (Tables 1 & 2). While heat treating the steels one important question arises is : what is the optimum microstructure which will give maximum long term creep strength coupled with creep ductility. Logically the bainitic microstructure could be considered as optimum but in practice it is neither always possible nor strictly desirable to have bainitic microstructure. First, because of the wide variation in the section size of the tubes and pipes. Second, it is interesting to note that ASME specification limits the hardness to 165 max. for these products i.e. the specification requires that the material should be in a reasonably soft state so that subsequent treatment, like joining of the tubes and bending of the tubes to form different types of bends which are inevitable in the fabrication of boiler, can be carried out without any difficulty. Obviously such low hardness can be obtained even in 100% ferritic structure in the conventional tubing materials. This is why a broad microstructure possessed by tubing and piping are seen in real life situation. Usually these tubes are commercially normalised at a temperature of about 910°C followed by tempering at 700°C. The microstructure developed depends on the wall thickness of the tubes.

However, metallurgists would ordinarily require to know how does creep strength vary with microstructure? A detailed study has been carried out at NML and the result is summarised in Fig. 2. A careful look on this figure would reveal that bainitic microstructure indeed has higher creep strength in so far as short term strength are concerned. However, in the low stress range of 32 to 50 MPa which is usually encountered in service, there is no appreciable effect of microstructure, in other words the long term strength say 100,000 hour or 200,000 hour rupture strength, does not seem to depend significantly on the initial microstructure.

HEAT TREATMENT OF HEAVY FORGING AND CASTING

Heat treatment of heavy forging and casting is certainly of importance so that the desired properties are achieved without introducing residual stress and dimensional changes beyond the limit. Here the critical factor is the mass of the forging/casting.

Tables 4, 5, 6 & 7 give the chemical composition and mechanical properties of important grades of casting and forging. Fig. 3 shows the CCT diagram for a typical grade. The heat treatment cycles are tailored to produce the desired mechanical properties.

Castings are austenitised in boggie-hearth furnaces and quenched in forced air or oil depending on section thickness. The castings are then tempered in order to get the desired properties. Fig. 4 gives a typical heat treatment cycle followed for a 210/500 MW steam tarbine casing made out of GS-17CrMoV511 steel. This treatment usually gives rise to bainitic microstructure.

The forgings undergo different heat treatment operations depending on their grade, size and property requirement. Rotors are heat treated in verticle condition and quenched in mist from jets fixed on verticle ramps. During quenching the rotors are slowly rotated. Diffusion annealing is carried out for reducing hydrogen content. Forgings are given preliminary machine operation before quality heat treatment for reducing the tendency of cracking on rough surfaces.

HEAT TREATMENT OF 12% Cr FOR TURBINE BLADE APPLICATION

In general, the high temperature applications of the 12% Cr stainless steel are not dependent on its high temperature strength alone, but rather on the combination of corrosion resistance, ability to be heat treated to a relatively high hardness level at room temperature and fair degree of high temperature strength up to 580^{0}C.

The heat treatment generally involves hardening (950-1100^{0}C) followed by tempering (600-700^{0}C). However, it is interesting to know that the response of heat treatment is not similar for all the heats of 12% Cr type. In other words, the composition remaining within the specified limit, the properties can vary widely. Fig. 5 shows the range and average values obtained for 7 different heats. For 1000^{0}F (538^{0}C) temperature, the spread in impact resistance is from 10 to 90 ft.lb, a difference of 9 to 1. This spread decreases as the tempering temperature is increased, specially above 1150^{0}F (621^{0}C), and for a temperature at 1250^{0}F (680^{0}C), the difference is only of the order of 20 ft-lb. These same 7 heats were found to display a considerable variation in their hardness values after being given tempering treatment. Therefore, close control of the steel composition is required if a specified minimum impact resistance must be obtained for a specified minimum hardness. For example, one specification requires that steel heat treated to a hardness range of 200 to 290 brinnel must possess the minimum impact resistance of 30 ft-lb. If all 7 dheats of Fig. 5 are considered, the range in impact resistance for this specified hardness range could be from 20 to 100 ft-lb. In other words, some of these heats would not meet this specification.

It is reported that presence of free ferrite in 12% Cr steel will increase the impact resistance after tempering. The effect of free ferrite is shown in Fig. 6. One of the heats contain no free ferrite and the other had 35% ferrite.

The importance of free ferrite in improving the impact resistance of 12% Cr type steel is fully recognised and this is the reason that in certain specifications ferrite forming elements like Mo up to 0.5% is added to ensure the presence of free-ferrite.

12% Cr steels are susceptible to decarburization during heat treatment. Thus heat treatment in inert atmosphere (endothermicones) or in salt baths is the most common of avoiding decarburization. Cracked ammonia or nitrogen is unsuitable because nitriding occurs. Ausforming and marstraining, both of which add the strengthening effect of mechanical working to that resulting from heat treating, have received considerable attentions, especially in connection with turbine blades, pressure vessels and rocket-meter cases. While strengthening is directional the strength advantage appears sufficient to warrant further exploration (Fig. 7).

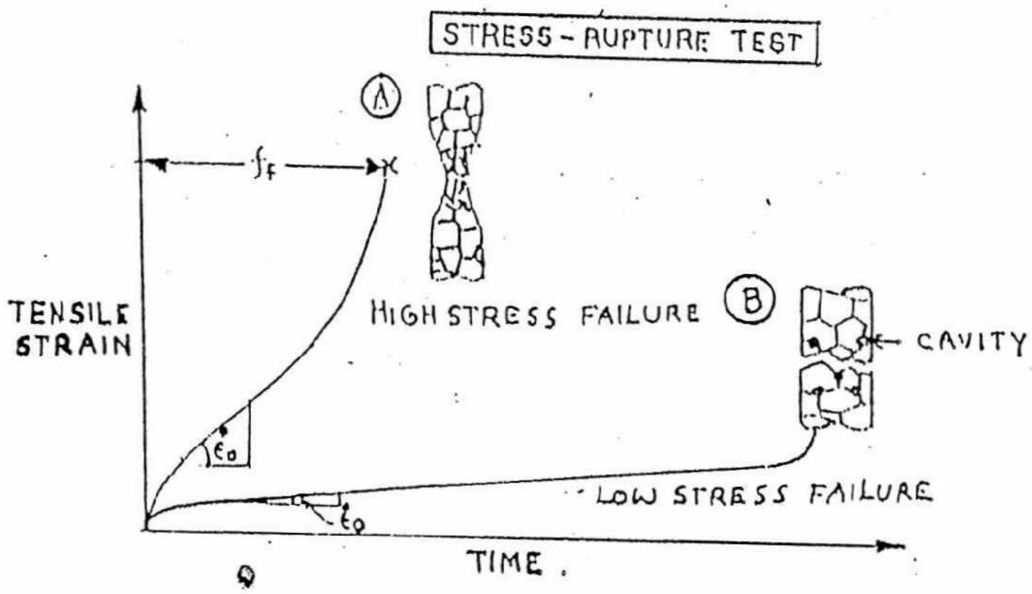
Ausforming is carried out at 400-700^{0}C and in some cases at 980^{0}C if the deformation was rapid. The strengthening increases with the amount of deformation and is retained on tempering upto 700^{0}C. However, there occurs slight loss of tensile ductility and some decrease in resistance to crack propagation.

In marstraining, a small plastic strain (about 0.4%) is imposed on a quenched and tempered steel followed by retempering or aging. Marstraining generally produces an increase of about 15% in yield strength.

CONCLUDING REMARKS

It can be seen that for tubing and piping the creep resistant steels are heat treated to give rise to "soft" structure. On the other hand, the rotating components of the turbine where high tensile strength/impact strength is of importance, they are heat treated to produce "hard" structure. In case of heat treatment of forging and casting, the critical factor is the huge mass of the component which calls for careful control of rate of heating/cooling, uniformity of heating all along the surfaces etc.

CREEP FRACTURE
(PHENOMENOLOGY AND MECHANISM)



HIGH STRESS (A) LOW STRESS (B)

TWO POSSIBLE MECHANISM OF FAILURE :

(A) NECKING (B) CAVITATION

PARAMETERS CHARACTERISING STRESS-RUPTURE TESTS :

(1) MINIMUM CREEP RATE ($\dot{\epsilon}_0$) (2) TIME-TO-FRACTURE (t_f)

CRITERIA OF FAILURE OF A COMPONENT :

(1) DEFORMATION LIMIT (SAY 1% CREEP)

(2) TIME TO FRACTURE ($1 \times 10^5 - 2 \times 10^5$ Hr.)

NORTON'S CREEP LAW

(POWER CREEP LAW) :

$$\dot{\epsilon}_0 = A\sigma^n$$
$$= A(\sigma - \sigma_0)^n$$

A = CONSTANT

n = CONSTANT (=4)

σ_0 = FRICTION STRESS

Fig.1 : Creep Phenomenon and Related Aspects.

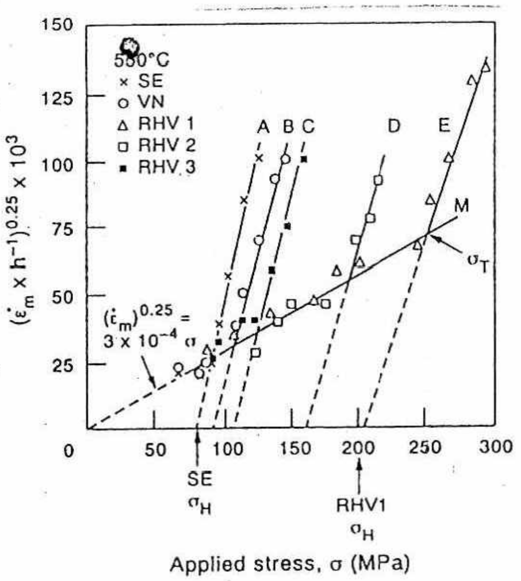


Fig. 2 Threshold stress for different microstructures in 1Cr–0.30 Mo–0.25 V steel.

Table 1. Details of the 1Cr–0.3Mo–0.25 steel samples investigated

Sample	State/ dimension	Heat treatement	Microstructure	Hardness (HV)
VN	Virgin pipe: 273 mm OD × 22 mm thick	Commercially N at 980° + T at 700°C	90% ferrite + 10% bainite	156
SE	Same as VN but service exposed at 540°C/50 MPa (hoop stress)	—	90% ferrite + 10% tempered bainite	152
RHV1	15 mm dia bars prepared from the VN material	Austenitized at 980°C (1 h) followed by oil quenching and T at 700°C (2 h)	100% bainite	210
RHV2	As RHV1	N at 980°C (1 h) + T at 700°C (2 h)	80% ferrite + 20% bainite	190
RHV3	As RHV1	N at 980°C (1 h) + T at 700°C (72 h)	80% ferrite + 20% tempered bainite	160

N—normalized; T—tempered.

(Ref. R. Singh & S. Banerjee, Acta Metall Mater, Vol.40, No.10, P.2607).

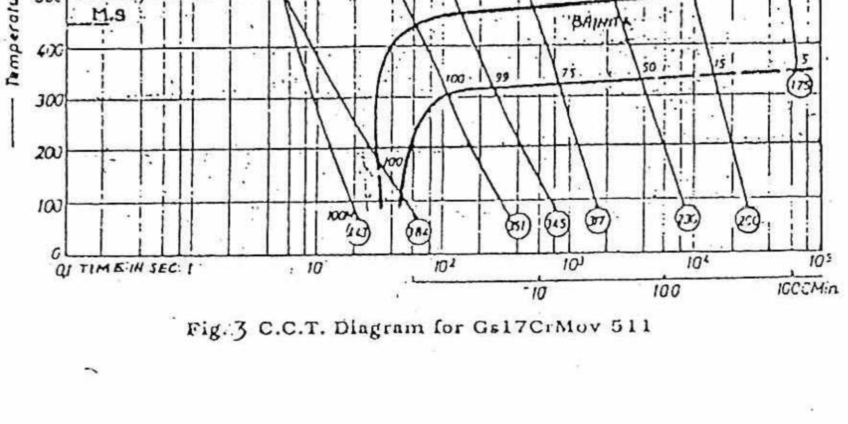


Fig. 3 C.C.T. Diagram for Gs17CrMov 511

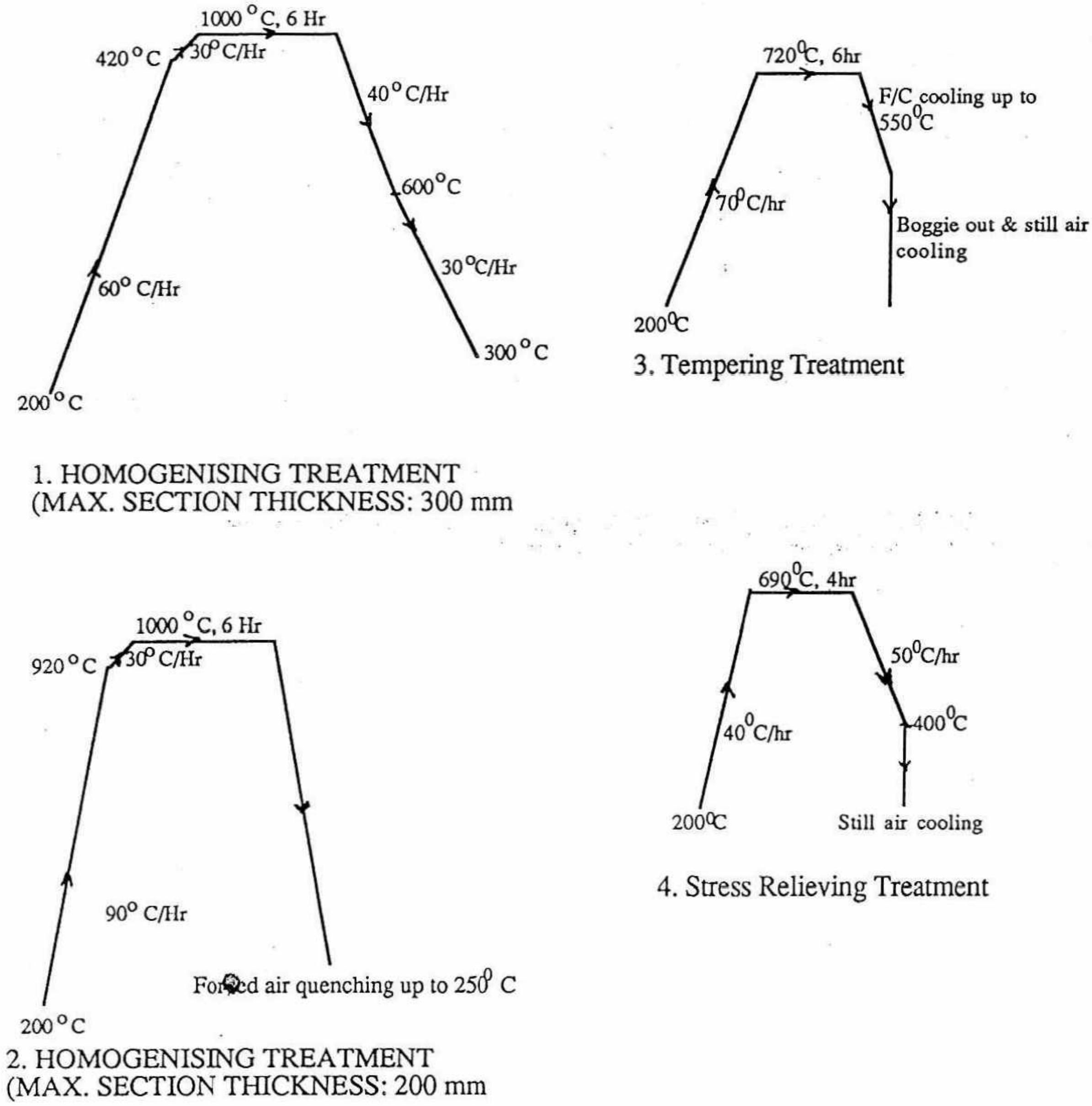


Fig. 4. Typical Heat - Treatment Cycle Followed for a Steam Turbine Casing (Gs17CrMoV511)

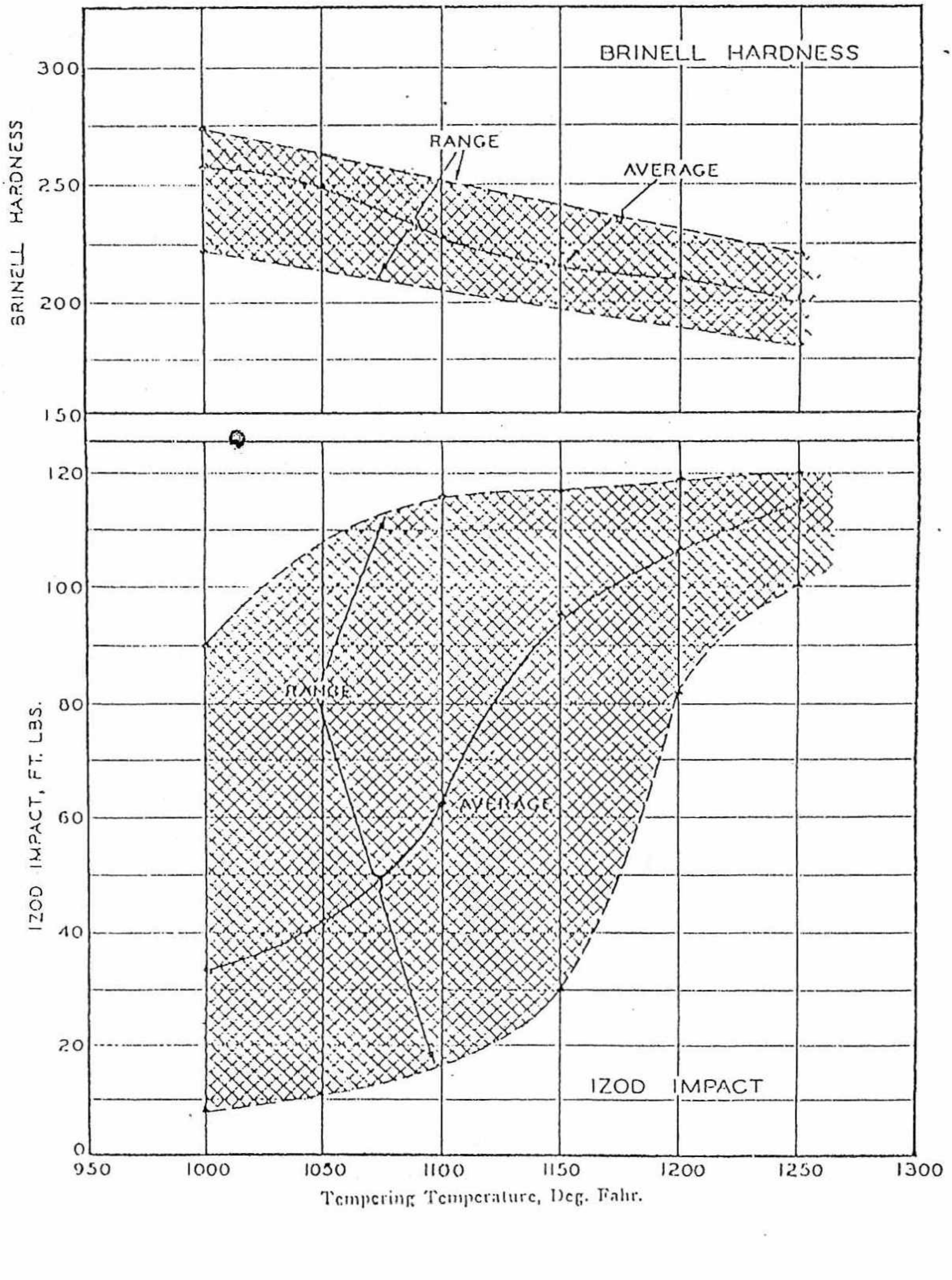


Fig.85 : Variations in Room Temperaure Hardness and Impact Strength After 6-Hour Tempering Treatment of Oil-Quenched (1800 °F) Type 410 Steel.

The spread in Impact strength is great, whereas variations in hardness are minor.

(Ref. Course 16, High Temp. Metals ASM)

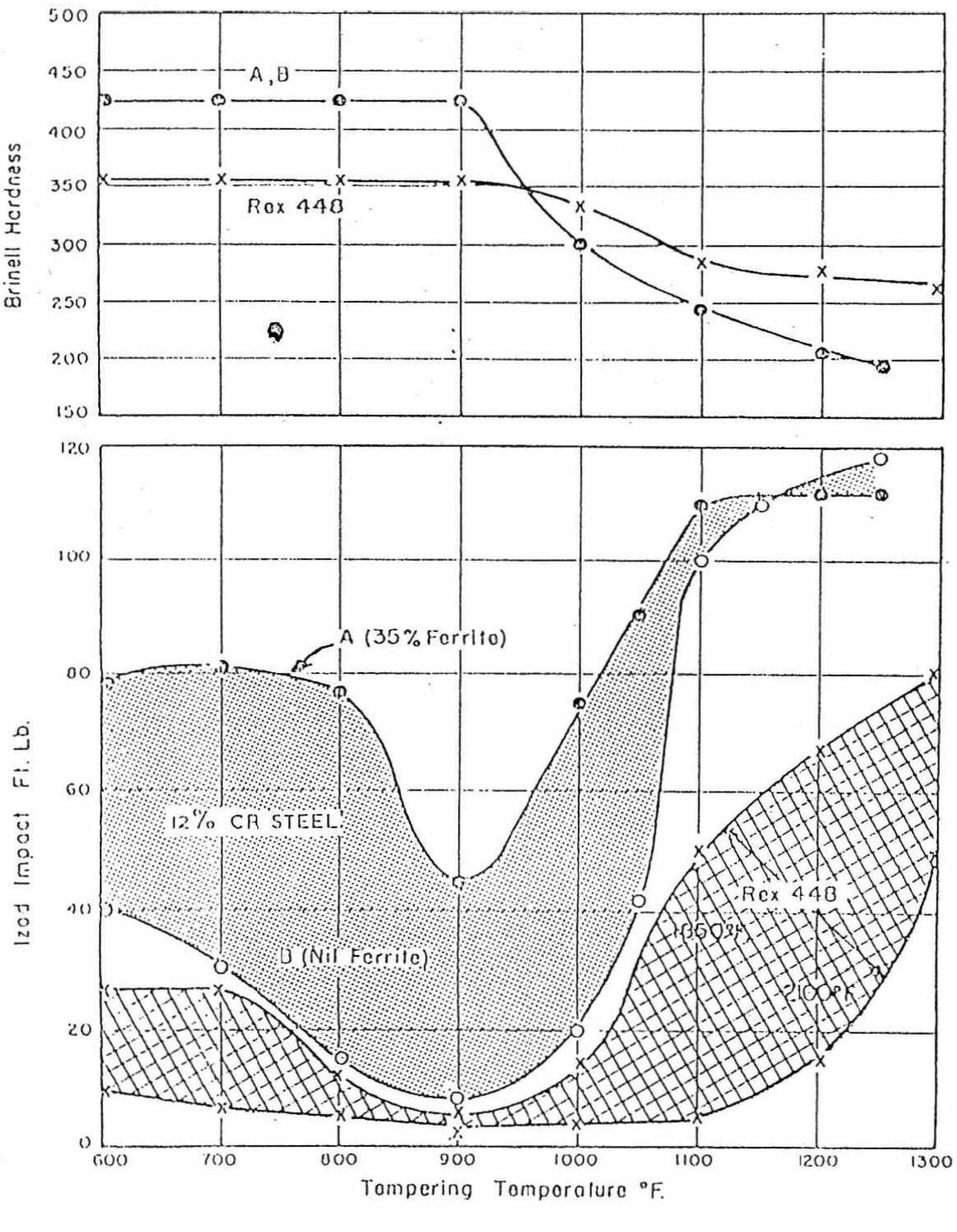


Fig. 6: Effect of Ferrite on Impact Strength and Hardness of 12% Cr Stainless Steel.

Specimens were tested at room temperature after oil quenching and tempering for 6 hours at the temperatures indicated.

(Ref. Course 16, High Temp. Metals ASM)

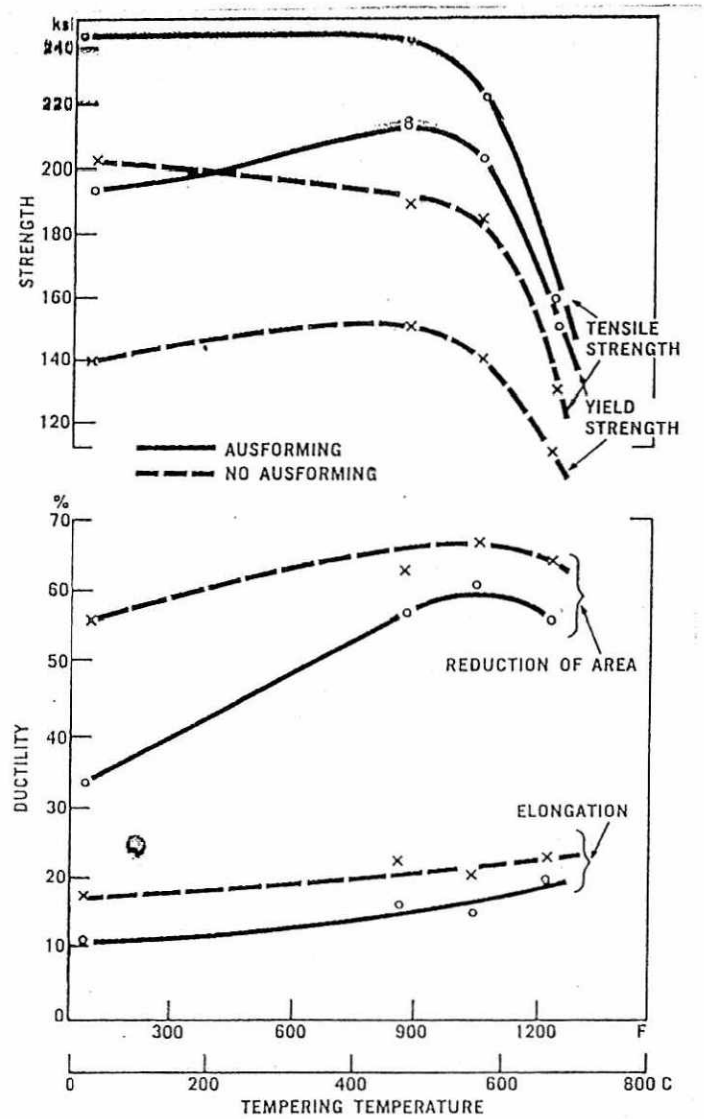


Fig.7 : Improvement in tensile strength after ausforming 12% Cr steel.
(Ref. The Super 12% Cr Steel Climax Molybdenum Page 167)

TABLE 1: CHEMICAL COMPOSITION, END USE AND SPECIFICATION OF SOME Cr-Mo-V STEEL

Steel Grade	Chemical Composition (wt%)									End use	Specification
	C	Cr	Mo	V	Si	Mn	S	P	Others		
1. 0.5Cr-0.5Mo-0.25V	0.10/ 0.18	0.30/ 0.60	0.50/ 0.70	0.20/ 0.35	0.40/ max.	0.40/ 0.70	0.04/ max.	0.04 max.	-	1,2	ISO TS33
2. 1Cr-0.3Mo-0.25V	0.08/ 0.15	0.09/ 1.20	0.25/ 0.33	0.15/ 0.18	0.17/ 0.37	0.40/ 0.70	0.025 max.	0.005 max.	-	1,2	Russian grade (12khIMF)
3. 1.25Cr1 1Mo-NiV	0.28/	1.1/	1.0/	0.25/	0.11/	0.58/	-	-	Ni 0.50/0.75	3	DIN 17240
4. 1Cr-1Mo-0.25V	0.17/ 0.20	1.20/ 1.50	1.0/ 1.2	0.25/ 0.35	0.30/ 0.50	0.30/ 0.50	0.035 max.	0.035 max.	-	4	DIN 17240
5. 1Cr-1Mo-0.75V-Ti-B	0.17/ 0.24	0.90/ 1.40	0.80/ 1.10	0.7/ 1.0	0.35 max.	0.50 max.	0.025 max.	0.025 max.	Ti 0.05/0.12 B 0.05 max.	4	GOST 2591
6. 1Cr-1Mo-0.75V-Ti-B	0.15/ 0.25	0.90/ 1.30	0.85/ 1.10	0.50/ 0.80	0.10/ 0.35	0.35/ 0.75	0.03 max.	0.03 max.	Ti-0.45/0.20 B-0.001/0.010	4	Durehete 1055 (U.K.)

1 - Superheater; 2 - Main Steam Pipe; 3 - Rotor, 4 - Bolting

TABLE 2 : CHEMICAL COMPOSITION, END USE AND SPECIFICATION OF Cr-Mo STEELS

Steel Grade	Alloy Composition - %							Specification
	C	Cr	Mo	Si	Mn	S	P	
0.50Mo	0.15-0.19	-	0.95-0.62	0.15-0.45	0.40-0.70	0.055 max	0.035 max	ASTM 213-T1
1Cr-0.5Mo	0.15 max	0.80-1.25	0.44-0.65	0.50 max	0.30-0.60	0.45 max	0.45 max	T12
1.25Cr-0.5Mo	0.80-0.15	1.0-1.5	0.45-0.65	0.50-1.10	0.30-0.60	0.04- max	0.04 max	T11
2.25%Cr-1%Mo	0.15 max	1.9-2.6	0.87-1.13	0.50 max.	0.30-0.60	0.05 max	0.03 max	T22

These are used for superheaters & reheaters

Table 3 : Martensitic and Austenitic Steels

Alloy Designation	Basic Composition	Applications
<u>Martensitic</u>		
12 Cr	12%Cr-0.1%C	Blading (L.P.)
12CrMoV	12%Cr-0.6%Mo-0.2%V-0.6%Mn-0.1%C	Blading (H.P.)
<u>Austenitic</u>		
18Cr8Ni(204)	0.05%C-18%Cr-8%Ni	SH tubing with
18Cr12NiMo(316)	0.5%C-18%Cr-12%Ni-2.5%Mo	Service Temperature > 600^0 C

TABLE 4

CHEMCAL COMPOSITION OF CREEP RESISTANT STEELS FOR CASTINGS

Designation	Average Compostion Percent											
	C	Si	Mn	S max	P max	Cr	Mo	V	Ni max	Al	Cu	Sn
GS-17 CrMoV 511	.17	.45	.65	.02	.02	1.35	1.0	.25	.50			
GS-18CrMo 910	.17	.45	.80	.025	.03	2.25	1.0	-	.50			
GS-22Mo4	.20	.45	.65	.02	.02	.30	.40	-	-			
15X1M1ф	.17	.30	.75	.025	.025	1.45	1.0	.32	.30			

TABLE 5

CHEMCAL COMPOSITION OF CREEP RESISTANT STEELS FOR FORGINGS

Designation	Average Compostion Percent											
	C	Si	Mn	S	P	Cr	Mo	V	Ni	Al	Cu	Sn
28CrMoNiV 59	.28	.10	.55	.01	.01	1.25	.90	.30	.60			
30CrMoNiV 511	.31	.10	.55	.01	.01	1.25	1.1	.30	.62			
21CrMoNiV 47	.21	.35	.60	.015	.015	1.25	.72	-	.60			
10CrMo 910	.15	.35	.50	.02	.02	2.25	1.0					

TABLE 6

MECHANICAL PROPERTIES (MINIMUM) OF CASTING GRADES

Designation	Proof Stress (0.2%)(Kg/mm²)	UTS (Kg/mm²)	% El. 1 = 5d	Impact ISO-V Joules
GS-17CrMoV 511	45	60	15	24
GS-18CrMo 910	40	60	18	40
GS-22Mo4	25	45	22	24
15XIMI ф	30	50	15	30 (2mm U)

TABLE 7

MECHANICAL PROPERTIES (MINIMUM) OF FORGING GRADES

Designation	Proof Stress (0.2%) (Kg/mm)	UTS (Kg/mm²)	% El. 1 = 5d	Impact ISO-V Joules
28 CrMoNiV 59	55	70	15	24
30 CrMoNiV 511	55	85 (Max)	15	24
21 CrMoNiV 47	55	70	15	24