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Influence of Overtempering on the Micromechanical Aspects of a Mn–Cr Steel Used in Turbogenerator

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Abstract. Overtempering characteristics of Mn–Cr steel used in retaining rings have been considered. The microstructures of the steel at various tempering temperatures have been determined. Mechanical properties at room temperature along with fractographic characteristics of the tensile and impact test specimens have been evaluated. The metallographic results show that massive carbide precipitation begins at 450° C onwards on stress relief. The mechanical test results indicate that the determination of the percentage reduction in area in tensile test, energy absorbed in impact test, and both tensile and impact fractographs give an accurate picture of the health of a retaining ring forging.

INTRODUCTION

Ring forgings made of austenitic and cold worked nonmagnetic steel are used for retaining the end windings on generator rotors. These rings are assembled on the rotor body by the shrink-fit method. These are used in yield strengths as high as 1200 MPa. Out of a few types of nonmagnetic steels, the 18Mn–4Cr type is most popular and several thousands of rings made of this composition are known to be in use all over the world [1].

The extraordinary strength required in the ring forging arises from the fact that it has to sustain various high stresses generated at the key ways. The magnitudes of these stresses for 600–1100 MW machines can be ascertained from Table 1 [2].

High strength of this nature is attained basically by cold deformation as part of a fabrication process comprised mainly of (a) solutioning of the cogged ingot to homogenize austenite, (b) water quenching to retain austenitic structure, (c) cold deformation to impart required strength, and (d) stress relief treatment [3]. Subsequently the ring undergoes repeated heating for shrink-on/off operation during the lifetime of the rotor, whenever it is sent to the generator assembly shop for repair and inspection. While the stress relief temperature is specified to be 300/350° C [3,4], the heating for shrink-on/off operation is normally limited to 250° C for ring expansion. However, the possibility of a ring becoming overheated either during stress relieving or during assembly operation exists, as a result of which the material toughness will be reduced and the ring can be made much more sensitive to stress corrosion cracking than if it were not overheated. Reprecipitation of carbide as a result of insufficient cooling after annealing and work hardening between 300° C and 900° C [3] and heat treatment between 300° C and 1000° C [5] has been reported in the literature for this steel. Speidel [6] has reported a dramatic fall in fracture toughness value on heating beyond 400° C. Authors have studied the influence of overtempering on metallurgical and mechanical aspects, which may help in improving upon the specification of material parameters for property requirements, in fixing an end limit on tolerance that may result in failure, and in improving upon the assembly operation at shop floor.

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MATERIAL AND EXPERIMENTAL PROCEDURES

Material

A retaining ring was obtained for the present studies from a generator manufacturing unit. This ring was not earlier put into service. The ring had a diameter of 1000 mm, an average thickness of 65 mm, and a length of 600 mm. The chemical composition of this ring is given in Table 2.

Table 1. A Relationship Between Retaining Ring Hoop Stress and the Generator Rotor Speed for 600–1100 MW Machines [2]

	0 (standstill)	3600 (normal operation)	4320 (over-speed)
Rotor speed, rpm			
Hoop stress, MPa	412.5–549.9	481.2–653.1	584.3–721.8

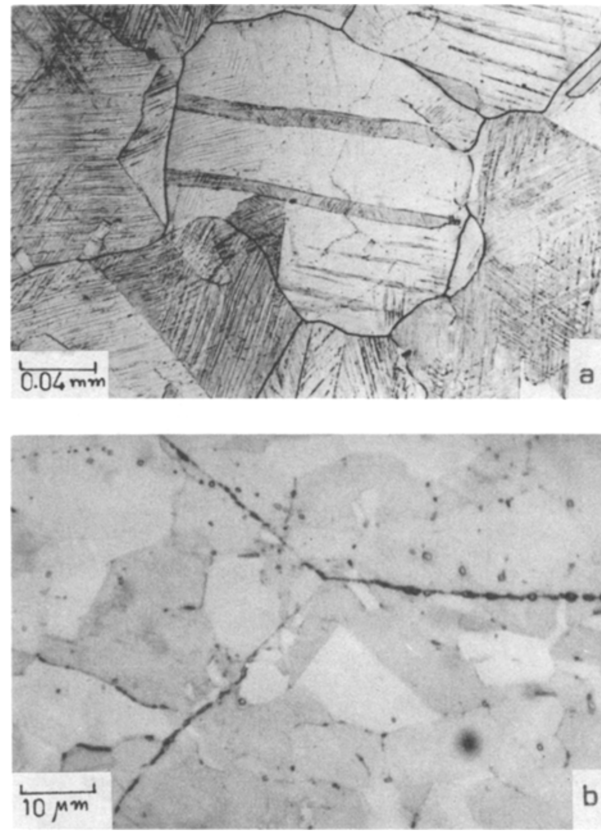

Fig. 1. Microstructures of the as-received specimen: (a) presence of large grains, twins, and deformation bands (chemically etched with 5% nital); (b) grain boundary carbide precipitation (electrolytically etched with 10% oxalic acid).

Specimen Preparation, Heat Treatment, and Test Methods

Tests were carried out with two categories of specimens. Specimens of the first category were prepared from the ring forging in its axial direction and were called as-received specimens. The second category of specimens were prepared according to the generally known method of processing a retaining ring forging made of nonmagnetic austenitic steel. Initially, 20 mm × 20 mm × 200 mm bars were sectioned from the ring. These were solutionized at 1040° C for 1 hr, water quenched, machined to round tensile bars, deformed in a (Materials Test System) servohydraulic tensile machine to 15% reduction of area as measured on the gauge diameter of the tensile bar, and stress relieved at different temperatures, namely 350° C, 400° C, 450° C, 500° C and 600° C. The stress relief of the specimens was carried out for 10 hr, following which these were furnace cooled. Solutionizing and stress relieving temperatures were maintained to less than ±5° C. The test specimens for tensile test were machined by carbide tipped tools using a machining procedure which would avoid formation of a rough and hardened surface. The notched Charpy impact specimens were prepared according to ASTM E 23. The V-notch was cut by electrode discharge machine using wire of 0.2 mm diameter. All tests were carried out at room temperature.

Tensile tests were carried out using an MTS servohydraulic tensile machine and impact tests were carried using a Tinius Olsen instrumented Charpy impact test machine. Fractographic studies were carried out using a Cambridge scanning electron microscope.

RESULTS AND DISCUSSIONS

Microstructural Aspects

Figure 1 shows the microstructures of the as-received specimen. The original ring forging microstructure is characterized by the presence of large grains (ASTM 0–2) [Fig. 1(a)]. The grain structure was also found to contain undissolved fine carbides, twins, and deformation bands. Besides, grain boundary carbide precipitation was also observed [Fig. 1(b)]. In contrast, the experimentally prepared microstructure consisted of fine grains which were reasonably uniform in size (ASTM 2–3). The microstructure also consisted of deformation bands and chains of prior carbides. The fine grain formation in the experimentally prepared specimen was obviously catalyzed by the cold worked nature of the ring forging which was used as starting material.

The presence of fine grains is an advantage in ultrasonic flaw detection since in presence of fine grains, ultrasonic waves can cut across the grains from one end of the forging to the other without much alteration

Table 2. Chemical Composition of the Retaining Ring, Wt%

C	S	P	Mn	Cr	Al	V	Ni	Si
0.52	0.01	0.02	18.98	3.87	0.035	0.05	0.15	1.04

in the process of identification of flaws within the material. It was observed that the carbides did not dissolve even if the solutionizing temperature was raised to 1080° C. Instead, the grain sizes were widely nonuniform under this condition.

A significant effect of temperature of stress relief was noticed on the microstructure. The microstructures (Fig. 2) indicated that up to a temperature of 400° C, there was no transformation of the steel on stress relief. The microstructure at this stage consisted of slip bands within austenitic grains along with preexisting carbides. But, from 450° C onwards, visible carbide precipitation was noticed. The extent of precipitation was massive at 500° C.

The size of the precipitates appeared to be coarse as compared to the prior carbides. As can be seen from the micrographs, the preferred sites of precipitation are grain boundary triple points, grain boundary lines, and the deformation bands existing within grains.

Mechanical Aspects

Mechanical tests were carried out to assess whether second-phase precipitation owing to excessive stress relief operation would affect the properties normally specified to characterize the retaining ring component. Test results were obtained as 0.2% yield strength (YS), ultimate tensile strength (UTS), percent elongation over 25 mm gauge length, and percent reduction in area over gauge diameter. These properties were determined for the as-received specimens as well as the experimentally prepared specimens. The results are given in Table 3. It is seen from the table that solution heat treatment leads to poor strength of the steel. The yield strength has more than doubled from 359.6 MPa to 749.3 MPa on work hardening. Fracture strength has also increased but not in proportion to the yield strength. For 15% reduction in area due to work hardening, the increase was 30% in fracture strength. Corresponding to this increase in strength, the reduction in elongation was from 64.3% to 35.4%, nearly 45%. Stress relief at 350° C improved the ductility with a marginal decrease in strength. It is noteworthy that no difference in room temperature strength occurs owing to stress relief up to a temperature of 600° C.

Even though elongation did not change up to 450° C, a drop in it was noticed with the 500° C and 600° C treatments, to an extent of 15.5%. This decrease in ductility can be attributed to embrittlement as a result of precipitation of carbides at the grain boundaries and deformation bands. But the largest effect of the precipitation was reflected on the percent reduction in area, from 54.3% at 450° C to 36.9% at 500° C and to 33.85% at 600° C, which constitutes a 37.6% drop of the reduction in area as a result of tempering at 600° C. The various effects of the stress relief temperatures on strength and ductility are shown in Figures 3 and 4.

Various tensile fracture characteristics as a function of stress relief temperature are illustrated in Figures 5 and 6. Figure 5 depicts general fracture pat-

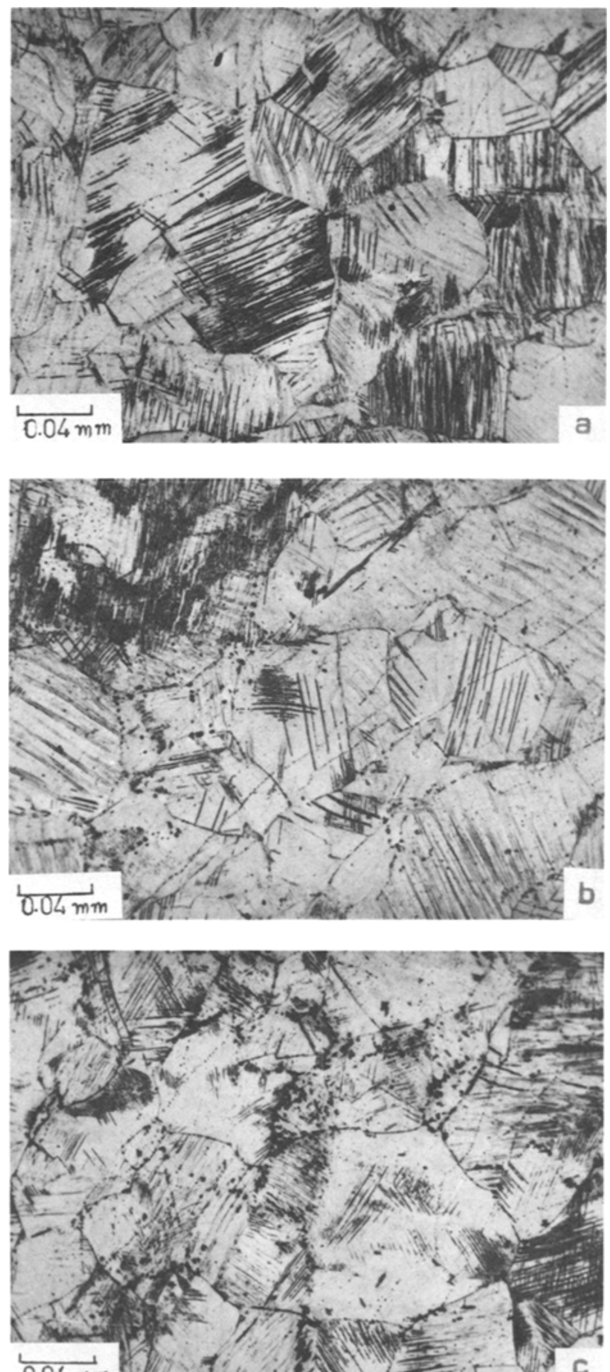

Fig. 2. Microstructures of the experimentally fabricated specimens stress relieved at (a) 400° C (b) 450° C and (c) 500° C. Carbide precipation can be noticed in (b) and (c).

Table 3. Tensile Test of the Retaining Ring Specimens

Specimen No.	Condition	0.2% YS, MPa	UTS, MPa	% Elongation, (Gauge Length = 25 mm)	% Reduction in Area
	As-received				
1		...	996.2	30.1	44.5
2		923.7	1141.9	27.7	41.0
3		898.9	1126.0	25.9	43.5
	Solutionized and water quenched				
4		378.5	813.7	72.5	53.4
5		359.6	804.3	64.4	47.5
6		378.5	813.7	61.1	54.3
	Solutionized, water quenched, and cold worked				
7		749.3	1053.5	35.4	52.0
8		759.0	1033.2	35.4	56.3
	Solutionized, water quenched, cold worked, and stress relieved at:				
9	350° C	690.8	1028.9	43.7	55.4
10		697.8	1012.9	44.2	58.4
11		697.9	1022.9	42.8	56.2
12		690.8	1019.4	44.0	56.3
13	400° C	702.6	1022.9	42.1	55.7
14		685.9	1008.9	46.1	56.3
15		697.8	1032.5	42.3	55.7
16	450° C	695.5	1024.1	42.3	55.0
17		707.4	1032.5	38.3	54.3
18		681.2	1019.4	35.7	36.9
19	500° C	690.8	1016.8	38.6	37.9
20		693.1	1027.7	39.6	42.4
21		662.9	1042.4	39.3	40.2
22	600° C	669.7	1041.5	24.9	30.4
23		658.2	1035.7	38.1	33.9
24		676.5	1048.0	35.5	33.8

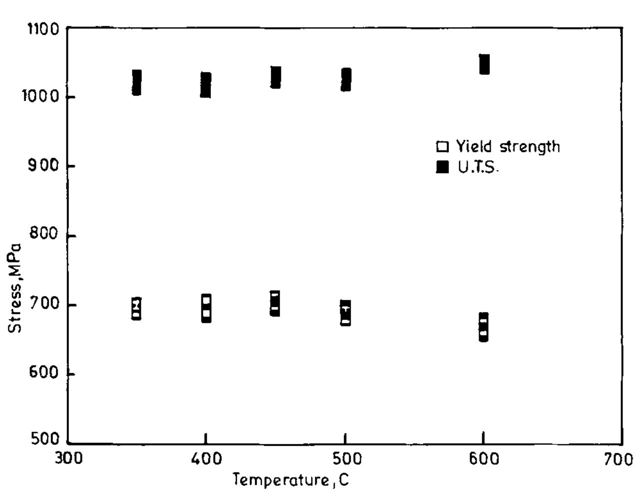

Fig. 3. Effect of stress relief temperature on UTS and 0.2% YS for the experimentally fabricated specimens.

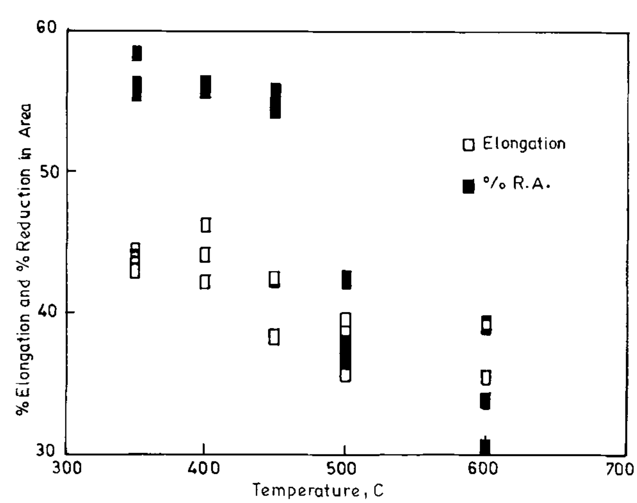

Fig. 4. Effect of stress relief temperature on ductility for the experimentally fabricated specimens.

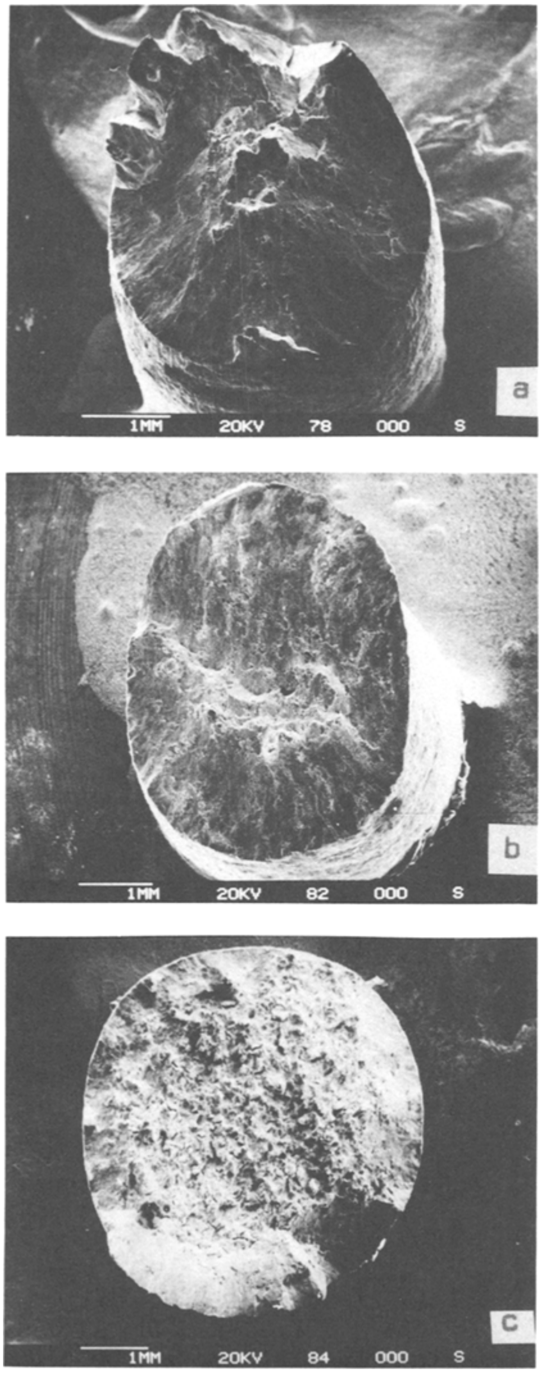

Fig. 5. Tensile fractographs of the experimentally fabricated specimens stress relieved at (a) 350° C (b) 450° C and (c) 500° C.

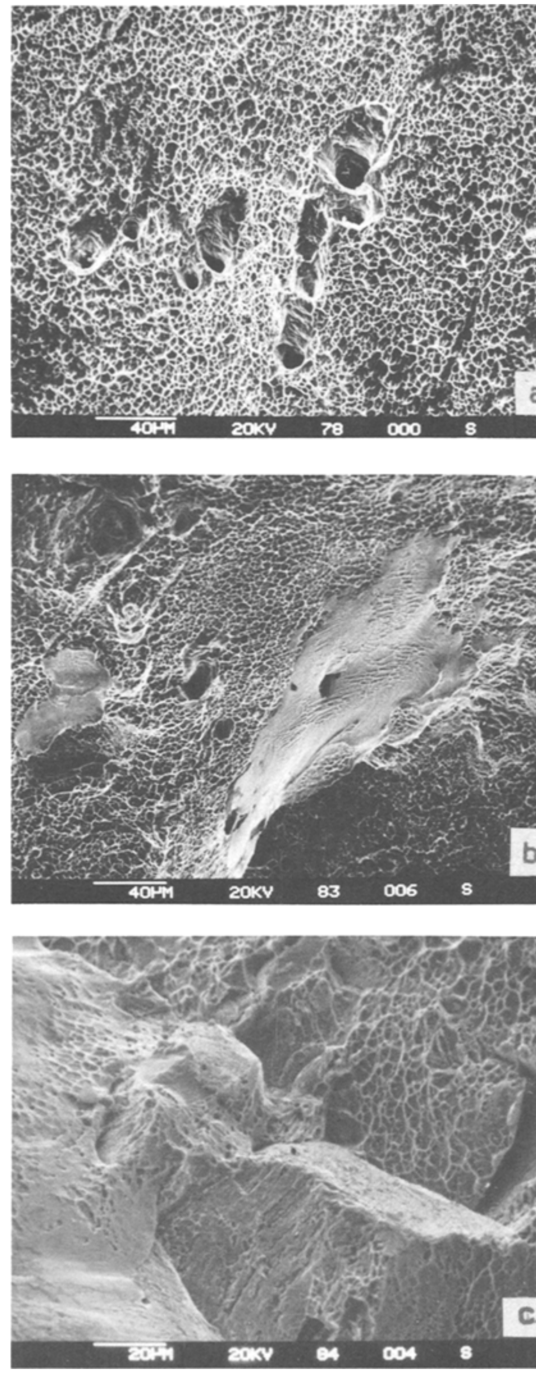

Fig. 6. Detailed fractographic illustrations of the experimentally fabricated specimens stress relieved at (a) 350° C (b) 450° C and (c) 500° C.

terns when stress relieved at 350° C, 450° C, and 500° C. The fracture is cup and cone at temperatures of 350° C and 450° C. It is flat and rough at 500° C. Detailed illustrations of these fractures are shown in Figure 6. It is noticed that at temperatures of 350° C and 450° C, the fracture is ductile with equiaxed dimples initiated at various voids, large and small. Some areas of fracture of the steel heated at 450° C are free from dimples and have a highly localized featureless fracture mode. At 500° C an intergranular rupture associated with flat and featureless surfaces and deep secondary cracks was noticed.

Therefore, a change of fracture mode from dimple to intergranular and an increase in the featureless fracture surface are associated with increasing stress relief temperature. Since an increase in the stress relief temperature leads to an increased amount of carbide precipitation, and its coarsening as was shown earlier, it is possible that the flat surfaces constitute a thin and continuous film of carbide precipitated at the grain boundaries.

Impact test data are an indication of the extent of toughness of the material when subjected to a high rate of loading. To assess the influence of overtempering under this condition, Charpy impact testing was performed both on the as-received specimens and on the experimentally prepared specimens which have different levels of work hardening. Table 4 shows the energies absorbed on fracture under different stress relief conditions. It is seen that the experimentally prepared specimens have a larger capacity to absorb energy before fracture as compared to the as-received conditions, since the experimentally prepared specimens were work hardened to a lesser extent during their preparation.

A plot of the test data (Fig. 7) indicates that:

1. In experimentally fabricated specimens in which the degree of work hardening is lesser, a sharp fall in absorbed energy values occurs at 500° C, whereas a similar fall occurs at 450° C in as-received specimens.
2. Energies absorbed before fracture are lesser for as-received specimens at a given stress relief temperature, which is an indication of their greater susceptibilities to embrittlement.

The impact fracture characteristics under different stress relieved conditions were compared between the as-received specimens and experimentally prepared specimens (Fig. 8). The fracture characteristics appeared to be nonductile from 450° C onwards in the as-received specimens, whereas the nonductile mode was visible from 500° C onwards in experimentally prepared specimens. Also, the kinetic condition for the precipitation process appears to be similar both at the grain boundary and the deformation bands for as-received specimens, as evident in the fractograph for the temperature of 500° C (Fig. 8). This is not so with the experimentally prepared specimens, where the precipitation at the slip bands became sufficient only when the temperature is 600° C. The reason is that a high amount of deformation associated with the as-received specimen causes the precipitation to occur as much at the slip bands as at the grain boundaries leading to brittle fracture characteristics which are intergranular and fibrous in nature.

Table 4. Impact Test of the Retaining Ring Specimens

Stress Relief Temperature, °C	Absorbed Energy, J	
	As-received	Experimentally Prepared
...	67,72	...
350	59,53,55	130
400	47,52,51	127,120
450	18,16,21	112,128
500	17,14	42,46
600	22,23	49

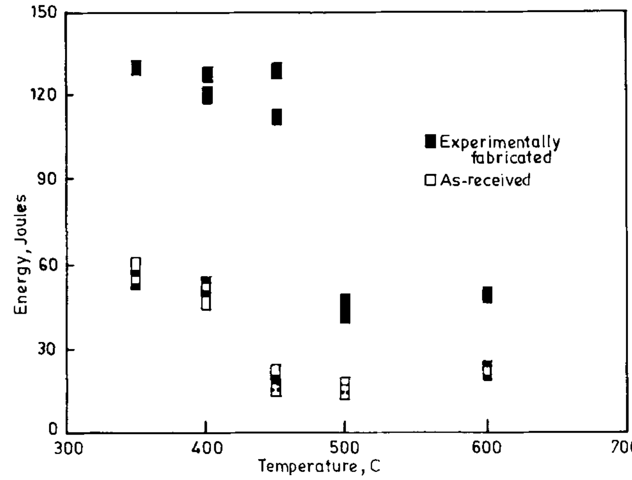

Fig. 7. Effect of stress relief temperature on the room temperature impact strength of the retaining ring steel.

CONCLUSIONS

1. Massive carbide precipitation at grain boundaries and deformation bands was noticed at stress relief temperatures of 450° C onwards for experimentally fabricated specimens.
2. Tensile strength data such as UTS and 0.2% YS do not reveal the embrittled state of a ring arising out of improper stress relief thermal treatment. Ductility in terms of percent reduction in area and the amount of energy absorbed on impact reflect the correct state of a fabricated ring.
3. Embrittlement gives rise to a fracture which is intergranular under tensile load and intergranular as well as fibrous under impact load. Both tensile and impact fractographs can be considered as yardsticks for assessing the embrittlement of a retaining ring.

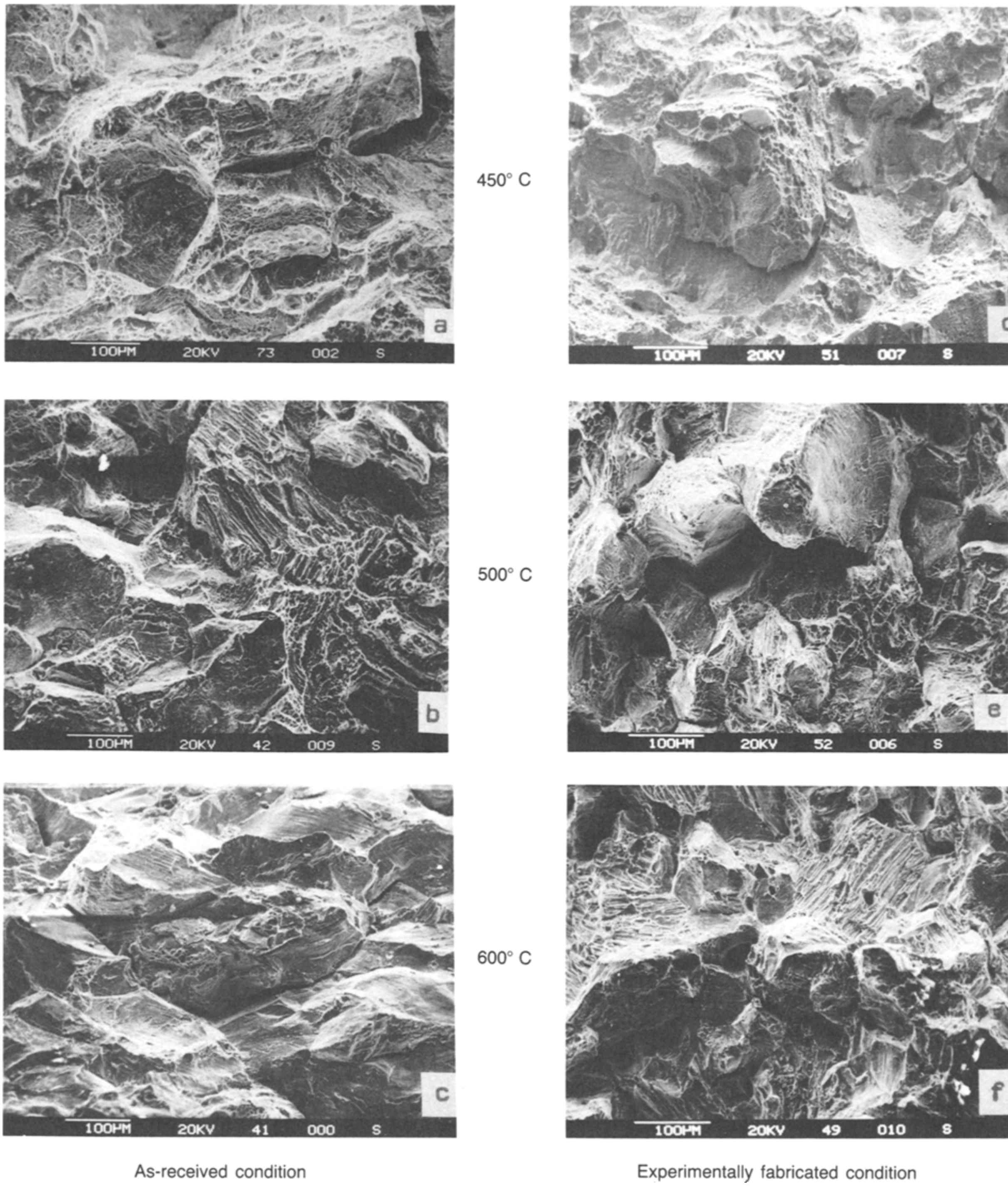

Fig. 8. Fractographic illustrations of the effect of stress relief temperature on the impact characteristics of the retaining ring steel work hardened to different degrees: (a),(b),(c): As-received condition. (d),(e),(f): Experimentally fabricated condition

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