# A New High Strength Steel for Generator Retaining Ring Application

R. VISWANATHAN, J. W. MORRIS, AND K. M. CHANG

*A new nonmagnetic steel with yield strength in excess of 200 ksi and plane strain fracture toughness ($K_{IC}$) in excess of 100 ksi $\sqrt{in.}$ has been developed by the Electric Power Research Institute in collaboration with the University of California at Berkeley. The alloy has good resistance to cracking in presence of hydrogen and chloride environments. The properties are obtained in the as-heat-treated condition without the need for cold expansion as has been the practice in the past. It is anticipated that successful commercialization of the alloy for use as retaining rings can result in improved generator reliability, size capability and efficiency. This paper is a progress report on this significant development.*

## INTRODUCTION

Retaining rings are massive ring forgings that are utilized in electrical generators to retain the circumferential arc portions of conductor coils as they emerge at the two ends of the rotating shaft. Figure 1 illustrates the function of retaining rings. The rings are subject to large centrifugal forces and are among the highest stressed components of generators, whose integrity is critical to the reliable and safe operation of the unit.

Retaining rings are currently made of an 18 Mn-Cr steel which is cold expanded, an operation which both forms the ring and work-hardens it to a yield strength of up to 175 ksi. There are three problems associated with this current practice. It does not now appear feasible to develop a yield strength much greater than 175 ksi in an 18Mn-5Cr retaining ring. This strength limitation places an upper limit on the size of electrical generators. If the electric power industry desires a further increase in generator size, retaining rings of higher strength will be required. While the hardened 18Mn-5Cr alloy appears tough in a normal fracture toughness test, it is susceptible to stress corrosion cracking in water, damp hydrogen, chlorides and other aggressive environments. This susceptibility to stress corrosion is believed to have been a major cause of several retaining ring failures experienced in service.[1] The need for cold-expanding the alloy to strength requires a complex and delicate manufacturing procedure and has resulted in a limited number of manufacturers of retaining rings.

To overcome the limitations associated with the current practice with Electric Power Research Institute initiated a project with the objective of developing a nonmagnetic heat heatable alloy which could achieve a yield strength of 200 ksi and fracture toughness ($K_{IC}$) of 100 ksi $\sqrt{in.}$ and which would be resistant to environmentally-induced cracking. This objective has now been achieved, on a laboratory scale, and an alloy designated as alloy $T$ has been developed. This paper summarizes the highlights of this development effort. In depth descriptions of

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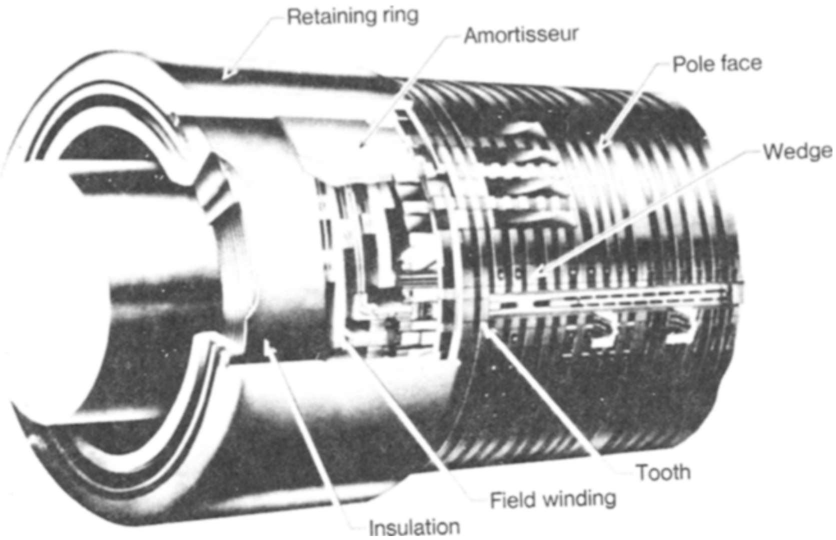


Fig. 1—Cut-away view of the end section of a generator rotor.

the physical metallurgy of the alloy, experimental procedures used in its evaluation and results may be found in other publications.[2,3]

## COMPOSITION AND HEAT TREATMENT OF ALLOY *T*

Alloy *T* has the nominal composition Fe-34.5Ni-5Cr-3Ti-3Ta-0.5Al-1Mo-0.3V-0.01B. The development of this alloy represents the successful culmination of a technical approach that required a rather sophisticated balance of composition and heat treatment. Special attention had to be paid to the precise precipitation chemistry, microalloy addition, aging process, and preaging condition in order to obtain an excellent combination of strength and toughness. Basically, the alloy development required improving the efficiency of precipitation hardening, and utilizing the full potential of precipitation hardening by suppressing intergranular precipitation and improving the kinetics of fine scale precipitation at low aging temperatures. The key compositional modifications involved were the additions of tantalum, chromium and molybdenum-vanadium-boron to the traditional Fe-Ni-Ti superalloy base. Tantalum was shown to significantly increase superalloy hardening through its incorporation in the $Ni_3X$ ($\gamma'$) phase precipitated during aging. Chromium was added to stabilize the austenite phase and to improve the resistance of the alloy to environmentally assisted cracking. The combination molybdenum-vanadium-boron was included to control grain boundary precipitation and to improve the ductility. The alloy contains extremely low amounts of carbon and is therefore not susceptible to sensitization type grain boundary damage, in sharp contrast to the 18Mn-5Cr steel. The heat treatments employed variations of the so-called double-aging process, in which the alloy is aged first at a relatively high temperature to initiate precipitation, then at a lower temperature to obtain significant additional hardening while suppressing cellular precipitation at grain boundaries. Based on detailed studies of the kinetics of precipitation, a double aging treatment of 1382 °F/4 h and 1238 °F/6 h following the forging at 2012 °F was identified to be the best processing sequence for the alloy.

## MECHANICAL PROPERTIES OF ALLOY *T*

Table I lists the mechanical properties of alloy *T*. These properties are based on 20 lb. laboratory heats made by vacuum induction melting using high purity raw materials. The ingots were forged at 2012 °F into plates, heat-treated using the double aging treatment and then evaluated for mechanical properties. In Table I, data on 18Mn-5 Cr steel are also provided for comparison. Data on 18Mn-5Cr steel are derived from plots contained in the ring manufacturer's literature and pertains to the highest yield strength material (175 ksi) for which information is available. The fracture toughness data on 18Mn-5Cr are based on a search of literature, as reported in Ref. 1.

**Table I. Mechanical Properties of Alloy *T* Compared with 18Mn-5Cr Steel**

| Property | Alloy *T* | 18Mn-5Cr Steel |
|---|---|---|
| 0.2 pct yield strength, ksi | 201 | 175 |
| Ultimate tensile strength, ksi | 228 | 180–210 |
| Elongation, pct | 16 | 18–40 |
| Reduction of area, pct | 53 | 30–40 |
| Cv-absorbed energy at room temperature, ft-lbs | 20 | 0–50 |
| Plane strain fracture toughness, $K_{IC}$, ksi $\sqrt{\text{in.}}$ | 103 | 64–133 |

It can be seen from Table I that the target values of 200 ksi yield strength and a $K_{IC}$ of 100 ksi $\sqrt{\text{in.}}$ have both been achieved. In the case of 18Mn-5Cr steel, the yield strength of 175 ksi is the upper limit of what is achievable in the material with the current state of the art. Despite its higher yield strength, the ductility and fracture toughness values of alloy $T$ are generally comparable to those of the 18Mn-5Cr steel.

## ENVIRONMENTAL TESTING OF ALLOY *T*

To evaluate the hydrogen sensitivity of alloy $T$, notched tensile and precracked compact tension fatigue specimens were tested comparatively in air and hydrogen using specimens heat-treated to the fully hardened condition. The results of the tensile tests are present in Table II, and show that there is no apparent influence of hydrogen gas on the notched tensile properties. Fatigue tests* were conducted using precracked compact tension specimens and using displacement control to ensure a cyclic crack opening displacement corresponding to a stress intensity at the crack tip which cycled between 0.1 and 0.6 of $K_{IC}$ at a frequency of 1 cycle/s. In this geometry, the maximum load automatically adjusts to ensure a constant crack opening which decreases in proportion to the crack propagation distance. The slope of the load *vs* cycles curve is a measure of the crack growth rate. Results of these tests, see Fig. 2, show the crack growth rates to be the same for alloy $T$ in hydrogen and in air. No magnetic martensite was detected on the fracture surfaces of any of the specimens tested in hydrogen. Relevant scanning electron microscopy revealed the failure mode to be ductile in all cases.

*Tests conducted by Dr. H. G. Nelson, NASA-AMES Research Labs, Mountain View, CA 94041.

In addition to tests in 0.8 atmosphere hydrogen, precracked compact tension specimens of the alloy have been subjected to subcritical crack growth testing in two environments: (1) 80 psig $H_2$ and (2) 50 psig $H_2S$. The test procedure differed from the conventional rising load test, in that load and displacement were applied cyclically in a series of increasing steps until clear evidence of crack growth was obtained.* The remainder of the test consisted of holding a constant displacement during continued growth of the crack under conditions of decreasing stress intensity $K$. Although the holding period was not long enough (1 to 3 days) to attain crack arrest, the rate of crack growth in each test declined to about $2 \times 10^{-5}$ in./min at the time of the test's termination. The values of stress intensity at this point were 72 and 67 ksi $\sqrt{\text{in.}}$ in $H_2$ and $H_2S$, respectively and are believed to denote $K$ threshold under those conditions. These $K_{Th}$ values are considered to be quite good since the test is believed to be a more severe type of test than the conventional rising load type test.

*These tests were conducted by Dr. F. C. Hull, Westinghouse Research Labs, Pittsburgh, PA 15235.

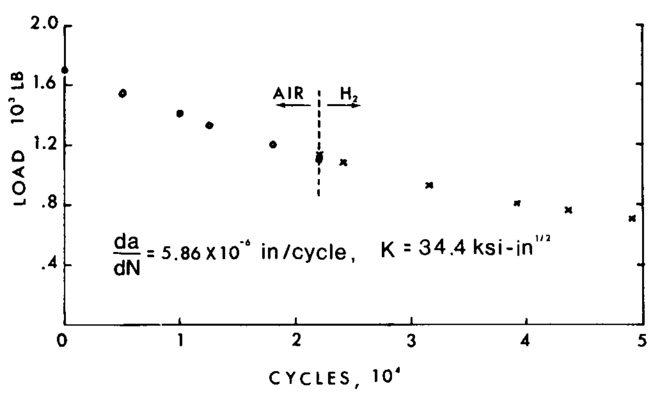


Fig. 2—Constant strain range fatigue tests on alloy $T$. Absence of abrupt slope change indicates same crack growth rate in air and in hydrogen.

**Table II. Results of Notched Tensile Tests of Alloy *T* in Air and in Hydrogen**

| Environment | Proportional Limit, ksi | Ultimate Stress, ksi | Plastic Extension ($\times 10^{-3}$ in.) |
|---|---|---|---|
| Air | 255 (1760) | 283 (1953) | 5.0 |
| $H_2$ (0.8 atm) | 255 (1760) | 293 (2022) | 5.0 |

Given the alloy's apparent resistance to gaseous hydrogen, its sensitivity to stress corrosion cracking in salt water was tested. For this purpose compact tension specimens 1/2 in thickness were made from fully hardened plate. Different crack lengths were introduced by fatigue at $\Delta K$ approximately 30 ksi $\sqrt{\text{in.}}$ The specimens were then stressed in a 3.5 wt pct aqueous sodium chloride solution under a dead load condition (3000 lbs.) on a cantilever bend rig with an arm ratio 10:1. The stress intensity established in the exposed specimen was then a function of the crack length, and ranged from 40 to 80 ksi $\sqrt{\text{in.}}$ for the various specimens tested. Stress intensities above 80 ksi $\sqrt{\text{in.}}$ could not be safely employed on these particular specimens since the limiting stress intensity for plane strain conditions in a 1/2 in. thick specimen of 200 ksi yield strength material is 89 ksi $\sqrt{\text{in.}}$ under ASTM guidelines. All specimens were dead weight loaded in salt water for one week. No crack growth was observed in any of the specimens, suggesting that the $K_{ISCC}$ of the alloy exceeds 89 ksi $\sqrt{\text{in.}}$ On the basis of the environmental tests it seems safe to conclude that alloy $T$ has good resistance to environ-

**Table III. Physical Properties of Alloy *T* Compared with 18Mn-5Cr Steel**

| Property | Alloy *T* | 18Mn-5Cr |
|---|---|---|
| Density, lb/in.$^3$ | 0.297 | 0.284 |
| Thermal expansion coefficient, °F$^{-1}$ | $15.8 \times 10^{-6}$ | $14 \times 10^{-6}$ |
| Resistivity, $\mu\Omega$in. | 29.64 | 29.84 |
| Magnetic susceptibility: | <1.01 | 1.005 |
| Elastic modulus, psi | $27.1 \times 10^6$ | $29 \times 10^6$ |
| Specific heat, Btu/lb °F | Not determined | 0.139 Btu/lb °F |
| Thermal conductivity, Btu/ft h °F | Not determined | 18 |

mentally induced cracking. Results published by Spiedel show that $K_{ISCC}$ of 18Mn-5Cr steel even in distilled water may be as low as 6 ksi $\sqrt{\text{in.}}$[4]

## PHYSICAL PROPERTIES

A number of physical properties which were believed relevant to the use of alloy *T* in generator retaining rings were measured. These included density, coefficient of thermal expansion, resistivity, magnetic susceptibility, and elastic modulus. All measurements were taken on the alloy in the fully-hardened, double-aged condition described earlier. The measured data are listed in Table III. The values obtained are in all cases typical of the known physical properties of commercial Fe-base superalloys. A comparison of the properties of alloy *T* with those of 18Mn-5Cr is shown in Table III.

The only physical parameter which warrants special discussion in terms of the suitability of alloy T for use in generator retaining rings is its coefficient for thermal expansion, which is a relevant property since retaining rings are one-piece forgings which are shrunk fit on the generator rotors, traditionally at 400 °C. The thermal expansion coefficient of alloy *T* ($15.8 \times 10^{-6}$ in./in. °C) is somewhat lower than that of the 18Mn-5Cr alloy now in use, which suggests the possibility of a problem if the same shrink fitting temperature is used. However, alloy *T* is strengthened by intermetallic precipitates and consequently has much greater thermal stability in its yield strength than does the cold-worked 18Mn-5Cr steel. There would appear to be no reason why the overall thermal expansion required to seat the retaining ring onto the rotor could not be attained simply by heating the retaining ring to a somewhat higher temperature.

## FUTURE WORK ON ALLOY *T*

The results obtained so far on alloy *T* have been on laboratory scale 20 lb heats. The problems that might arise in making commercial sized ingots and fabricating rings have to be explored. A first step in this direction has already been taken by producing a 300 lb ingot by vacuum induction melting and vacuum arc remelting. No difficulties have been encountered in makings the heat or in forging it. Tensile tests show that a yield strength of 205 ksi can be achieved in the solution annealed and double aged condition, without the need for retaining any of the hot forge work. If some of the forging work could be retained as was done with the 20 lb heat experiments, the alloy has the potential to achieve even higher yield strength levels. More extensive tests are needed before we can make firm pronouncements regarding there environmental susceptibility of the alloy. A major concern with alloy *T* is the price of the alloy. The presence of tantalum in the alloy makes it expensive relative to the current alloy. Experimental evidence generated during this study, however, indicates that tantalum may be replaced by niobium without significantly degrading the properties. Studies of the economic trade-offs may also show that the use of alloy *T* may be justified despite its high cost in view of a very favorable cost-to-benefit ratio. A more detailed characterization of environmental susceptibility alloy *T*, substitutions of other elements for tantalum in alloy *T*, scale up of the alloy to make and demonstrate commercial size rings and the economic trade offs resulting from the use of reliable higher strength retaining rings: these are issues that are being addressed in an ongoing EPRI study under contract to the General Electric Co.


## ACKNOWLEDGMENTS

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