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Challenges in Design and Development of Steam Turbine Rotors with Alloy617(M) for Indian AUSC Program

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***Abstract*— Fossil fueled thermal power plants are a major source of CO_2 emissions in atmosphere causing global warming. India as a responsible global partner committed to a green environment for future generations, has worked aggressively in the direction of increasing the net efficiency of its fossil power plant fleet. All the upcoming fossil fuel power plants of India are with supercritical/ultra supercritical steam parameters. To create a competitive indigenous technology catering the ever rising power demand of the country and to make the fossil power highly efficient and clean energy source for electricity generation in future, India has embarked upon the development of Advanced Ultra Supercritical (AUSC) power plant. Since, high pressure (HP) and intermediate pressure (IP) steam turbine components in these power plants are subjected to very high steam parameters, their robust design is pertinent for the success of the AUSC project. HP/IP rotors of AUSC steam turbines are planned to be dissimilar metal weld constructions. In these rotors Alloy617(M) will be used in the initial stages of turbines, where temperature will be above the capability of existing 10%Cr steels (around 600° C) used in supercritical turbines. This paper discusses the challenges faced in design and development of steam turbine rotors with material Alloy617(M).**

Keywords*— *Steam turbine rotors, Advanced Ultra Supercritical (AUSC), Alloy617(M)

I. INTRODUCTION

India is the world's third largest producer and fourth largest consumer of electricity. All India installed capacity of power stations is 330.26 GW as on May 31' 2017, comprising 195.6 GW of thermal. [1] As per the Integrated Energy Policy of the Government of India (August 2006) "by 2031-32 power generation capacity must increase to nearly 800 GW".[2]

India has the fifth largest coal reserves in the world.[3][4] Considering the electrical power generation targets of India and availability of vast coal reserves, fossil power is expected to remain the primary source of electricity generation in the country at least for the next few decades. Hence, India needs to adopt high efficiency coal-based power generation technologies in future to combat menace of CO_2 emissions and global warming, a major source of concern of fossil fuelled power plants.

To minimize CO_2 emissions from fossil power plants, a national mission for the development of AUSC technology has been initiated by Government of India (GoI). The development work is being executed by a consortium of three organizations: Bharat Heavy Electricals Limited (BHEL), Indira Gandhi Centre for Atomic Research (IGCAR), and National Thermal Power Corporation (NTPC).[7] Recently Government of India approved the proposal of R&D phase for development of Advanced Ultra Super Critical (AUSC) Technology .[8] The final mission objective is to successfully install and operate a reliable 800 MW demonstration AUSC power plant as early as possible.

Steam parameters of proposed Indian AUSC program are 310 kg/cm^2 / 710ºC / 720ºC. 10% Cr steels currently used in supercritical/ultra supercritical (USC) steam turbines can be used for operation with steam parameters up to 600 deg C. But, these steels exhaust their capability when temperature is further increased to the range of AUSC parameters i.e. more than 700 deg C. This led to consider the use of Nickel based alloys as candidate materials for use in AUSC steam turbine components.

Components of HP/IP steam turbines including their rotors are subjected to maximum steam temperatures. In Indian AUSC power plant, it is proposed to design HP/IP rotors with Nickel based forged material Alloy617(M) in the elevated temperature zone of turbines and 10% Cr steels in lower temperature zone with dissimilar welded joints between the two materials in the temperature zone below 600 deg C. This paper discusses the challenges faced in designing the rotor of AUSC turbines with material Alloy617(M).

II. MATERIAL SELECTION, DEVELOPMENT AND MANUFACTURING

For HP and IP rotors in steam turbines exposed to elevated temperature conditions, good creep rupture strength alongside enough hot yield strength is a primary requirement. In addition good ductility is generally desirable to take care of local plasticity at stress concentration zones. The criteria for selection of rotor materials for HP/IP steam turbines of AUSC power plant is based on

- Adequate high temperature mechanical strength, viz. average stress to rupture of 100 MPa for 10^5 hours at design temperature of component
- Good time independent strength properties (tensile)
- Good resistance to fatigue
- Moderate creep-fatigue interaction
- High thermal conductivity and low coefficient of thermal expansion
- High toughness, ductility and fracture resistance
- Defect detectability through NDT comparable with current practices
- Satisfactory corrosion resistance in steam environment
- Good formability and weldability

Apart from the above, it was preferred to consider materials included in ASME/equivalent International codes so that strong design basis for design of components, commercial suppliers at reasonable price and material properties to start the design are all available.[6] This would facilitate their indigenous development also. Based on above, preferred rotor material for application above 10%Cr steels capabilities was identified as Alloy617(M) (subset of Alloy617 specification of ASTM and data given in ASME). The main advantage of using Alloy617(M) instead of commercially available Alloy617 is around 20% higher creep rupture properties.

For development of materials and manufacturing technology, a pragmatic approach considering the existing industrial base and pace at which nation’s industrial capabilities can be enhanced is being adopted. Wherever possible, efforts are being made to indigenously produce advanced materials and manufacture components with these materials.[6] To prove the technological development and manufacturing process of dissimilar metal welded turbine rotors, it is planned to manufacture a full scale prototype rotor during R&D phase. Considering difficulties in machining Nickel based alloys, technical development for components manufacturing is one of the major objectives of R&D phase.

III. UTILITY OF AVAILABLE CODES FOR DESIGN

There are no internationally recognized standards for mechanical design of steam turbine components of fossil fuel power plants. One reason could be the complexities involved in design to take care of variety of operating conditions and functional constraints. The mechanical design of steam turbines is very complex as steam pressure is only one of the many aspects which need to be taken into account.[9] Standards like ASME BPVC, address mostly pressure retaining components in which the heat transfer takes place across the metals boundary only. While in steam turbines heat energy of fluid gets converted into mechanical energy of rotor which is finally converted to electrical energy. Even the pressure containers that are integral part of reciprocating or rotating mechanical devices are taken out from the scope of ASME BPVC.[10] Table 1 explains some major differences between pressure vessels/boilers and steam turbines, that lead to different design approaches for these components (please note that ASME section 1 only addresses the mechanical design aspect of power boilers not the overall design as whole).

TABLE 1: MAJOR DIFFERENCES BETWEEN DESIGN ASPECTS OF PRESSURE VESSELS/BOILERS AND STEAM TURBINES

Components covered by pressure vessel design codes	**Steam Turbines**
Retains pressure and heat transfer take place across metal boundary, no work is produced.	In addition to heat transfer, heat energy is converted into work.
Mostly static components, high cycle fatigue is not a major design criteria.	Dynamic machines. High cycle fatigue and rotor dynamics are major concern.
Normally components covered in codes are designed for safety and heat transfer is optimized (in boilers and heat exchangers).	Designed for a targeted efficiency along with functional aspects like compact design operating under close clearances. Higher material properties result in efficient and compact design.
Contain very high amount of energy (high equivalent TNT value). Hence failures are disastrous and safety is prime concerns. Design codes are available and subjected to legal binding.	Failures are disastrous but failure modes are not same as pressure vessel. Design is not regulated by codes. Best design practices are used.
Material properties used for design and design procedures are strictly as per code.	OEMs have their own design practices and materials are developed to suit their design requirements.
Although codes take care that materials selected should not be highly notch sensitive, still pressure vessels don’t have the type of notches found in steam turbine components e.g. blade grooves.	Blade grooves subjected to very high stress concentration, triaxial stress state and dynamic loads. Hence, notch effects are highly pronounced.
Heat transfer coefficients are very well established and experimentally verifiable through instrumentation.	It is extremely difficult to experimentally verify heat transfer coefficients on rotor surfaces and hence the transient temperature distribution. Conservative fatigue design procedure and material with high fatigue resistance are used.
As the volume of material used in boilers, piping, reactors etc. is very high, whatever best could be supplied by industries, complying the codes is accepted and design is carried out accordingly.	The volume of material used in a turbine is a small fraction of overall volume of material used in power plant and turbine design needs to be highly efficient. The best that could be produced across the globe with very stringent quality requirements is used.

It is evident from the above that pressure vessel design codes do not address the overall design aspects of steam turbines. Considering the fact that the materials selected for AUSC steam turbine are never used earlier for such applications, design rules/procedures of these well respected codes are used only as guidelines for elevated temperature design of steam turbine components. Proven design practices of earlier sub critical/super critical steam turbines are not compromised while adopting code practices. The generalized procedure of “Design by Analysis (DBA)” chapter of ASME-BPVC code was used for categorization of stresses and interpretation of results of finite element stress analysis.

IV. MATERIAL CHALLENGES

Since test data for candidate materials for forge components of Alloy617(M) was not available, limited material properties data was used from open sources and codes to start the design. Although a detailed material testing program is underway for material characterization of Nickel based alloys selected for Indian AUSC program, its findings will be utilized to validate the design data.

During the development of supercritical rotors made of 10% Cr steel, mechanical properties at operating temperature were similar to the operating temperature mechanical properties of low chrome steels of sub critical sets and they have been used successfully for many years.[11] But in case of AUSC turbine development the situation is not similar. Table 2 below compares the parameters of BHEL supplied subcritical and supercritical steam turbines with AUSC.

TABLE 2: EFFECT OF AGING AT 704 DEG C ON THE 0.2% YIELD STRENGTH AND % ELONGATION

	Main steam Temperature (deg C)	**Main steam pressure (bar)**	**Rotor material**
Subcritical	537	170	1-2% Cr steel
Supercritical	600	260	9-10% Cr steel
AUSC	710	310	Alloy617(M)

It can be seen from the above table, that increase in temperature from supercritical to AUSC is much bigger than that from subcritical to supercritical. Additionally, elevated temperature material properties of 10% Cr steels at 600 deg C are comparable to material properties of 1-2% Cr steels at 537 deg C, whereas material properties of Alloy617(M) are inferior at the proposed operating temperature 710 deg C in case of AUSC turbine.

For a cylindrical body of finite length with free ends (equivalent to steam turbine rotor) subjected to centrifugal loads, maximum rotational stresses occur at rotor center. Three principal stresses and equivalent stress due to centrifugal load at rotor center are maximum and are given by following formulae.[12]

$$\sigma_{radial,max} = \sigma_{hoop,max} = \frac{3-2\nu}{8(1-\nu)}\rho\omega^2 r_{outer}^2 \tag{1}$$

$$\sigma_{axial,max} = \frac{\nu}{4(1-\nu)}\rho\omega^2 r_{outer}^2 \tag{2}$$

$$\sigma_{von\ Mises,rotor\ center} = \frac{3-4\nu}{8(1-\nu)}\rho\omega^2 r_{outer}^2 \tag{3}$$

Where ρ is density of rotor material, ω is rotational speed, ν is Poisson's ratio and r_{outer} is rotor radius.

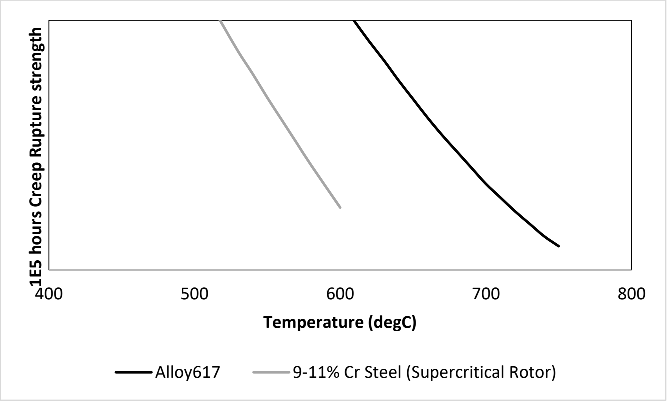

Fig. 1. comparison of 1E5 hours creep rupture

It can be seen that rotational stresses in rotor are proportional to density. Although 1E5 creep rupture strength of Alloy 617(M) and 10% Cr steels at respective operating temperatures are comparable (Fig. 1), the stresses encountered in Alloy 617(M) rotor due to rotation are 7% higher than 10% Cr steel rotor of the same size owning to higher density. Although pressure will relieve the rotational stresses but this advantage in stress calculation is not very significant and not accounted for to build conservatism in design.

- Center of Alloy617(M) rotor is having following additional challenges:
- Maximum rotational stresses appearing at the center of the rotor are primary in nature. They do not relax with time.
- Reduction in ductility under triaxial stresses is a well-known phenomenon. Stresses at rotor center are multiaxial in nature.
- Manufacturing of Alloy617(M) forgings of very large size is also not a matured technology and NDT of Nickel alloys is more challenging than existing Ferritic steels. Hence, detection of defect size at the center of the rotor, which is the most vulnerable location, is poor than existing Ferritic steel.

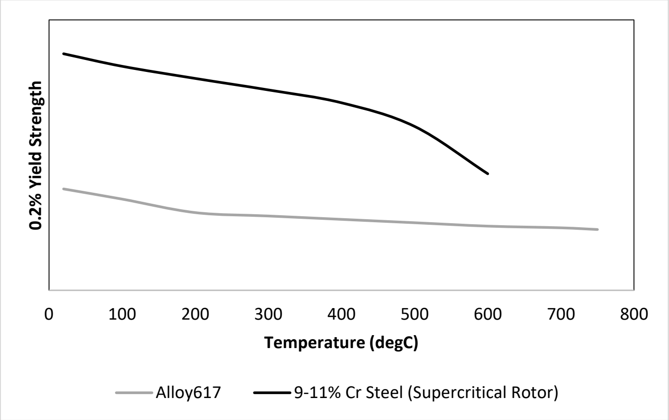

Fig. 2. comparison of 0.2% yield strength

Fig. 2 compares 0.2% yield strength of Alloy617(M) and 10%Cr steels used in supercritical sets. Alloy617(M) has lower hot yield strength in comparison to 9-11% chrome steels, this may cause reduction in margins for design against yield cases.

Many references in open literature suggest that aging significantly increases the yield strength of Alloy617. Sample data given in Table 3 is taken from ORNL/TM 9335.[13]

TABLE 3: EFFECT OF AGING AT 704 DEG C ON THE 0.2% YIELD STRENGTH AND % ELONGATION

Test Temperature = 704 deg C (in static air)				
Aging Condition		**0.2% yield strength (MPa)**	**% elongation**	**Remarks**
Temperature (deg C)	**Time (hours)**			
-	0	196	25.9	Specimens machined after aging
704	2500	256	14.4	
704	10000	211	16.9	
704	20000	285	13.3	

It can be seen that increase in 0.2% yield strength comes with a decrease in elongation. This behavior of material is being studied in consortium laboratories. This advantage in yield strength may be exploited in design.

In most of the engineering components stresses are proportional to load, hence factor of safety given in terms of ratio of operating stress to material's resisting capability (e.g. 0.2% yield strength in case of room temperature design, hot yield in case of over speeding event). Factor of safety is a number indicating how far is the component away from failure, which in most cases is measured as ratio of load carrying capability to applied load on structure. This is not true for rotors as primary stresses/loads are proportional to square of rotational speed. An increase of 10% in rotational speed will cause an increase of 21% in stresses. Hence, factor of safety against primary stresses for rotors is not an absolute indicator of its safety.

Turbines are designed for a specified life time (steady state operation) and with certain number of start-ups (transients). During start-up high transient thermal stresses which are secondary in nature are encountered causing low cycle fatigue. Hence, in each start, life of the components gets consumed. Start-ups of turbine are further subdivided in cold, warm and hot starts based on temperature of components at the onset of start-up In general cold start is maximum damaging. The fatigue design curves of draft ASME code case and limited test data generated by consortium are used for designing AUSC turbine rotors for low cycle fatigue.[14] Since fatigue properties of Alloy617(M) used for design of AUSC rotors are poorer than the fatigue properties of 10% Cr steels, the design is more challenging against transients.

Thermal stresses during turbine start-up are due to self-constraining of material due to temperature gradients. Thermal stress on a component may be given by

$$\sigma_{elastic\ thermal} = \frac{E.\alpha.\Delta T}{(1-\nu)} \tag{4}$$

Fig. 3 shows that the coefficient of thermal expansion of Alloy617(M) is higher than existing 9-11%Cr steels.

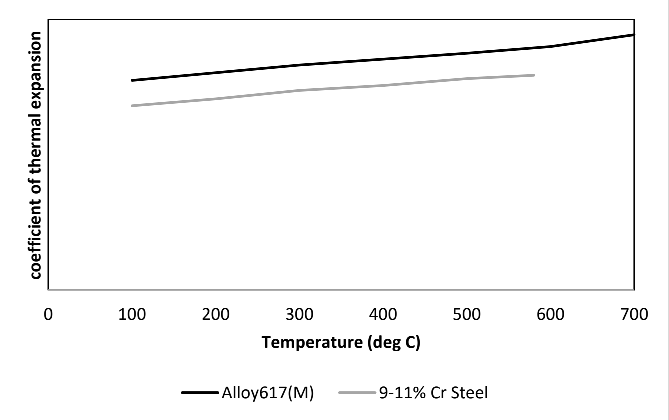

Fig. 3. Comparison of coefficient of thermal expansion

Where E is Young's modulus, α is coefficient of thermal expansion, ΔT is temperature difference between surface temperature and bulk mean temperature (which remains high during startups) and ν is Poisson's ratio. From equation (4) above, it is evident that for same temperature difference, higher coefficient of thermal expansion will result in higher thermal stresses.

The penetration rate of heat in material is a function of thermal diffusivity (k/ρ.C). Where k is thermal conductivity, ρ is density and C is specific heat. Temperature difference between two adjacent points of component depends on these thermo-physical properties of material and ramp rate.

Fig. 4 compares the thermal diffusivity of Alloy617(M) with existing 9-11% chrome steels. It can be seen that till 600 deg C (operating range of 9-11% Cr steels) thermal diffusivity of Alloy617(M) is lesser than 9-11% chrome steel and below 400 deg C this gap is very large. For a material with high thermal diffusivity, heat moves rapidly through it. Low value of thermal diffusivity combined with high coefficient of expansion results in high transient thermal stresses in Alloy617(M) during start-up. Hence number and duration start-up of turbine were modified to suite the design specifications and turbine will be designed as a base load machine.

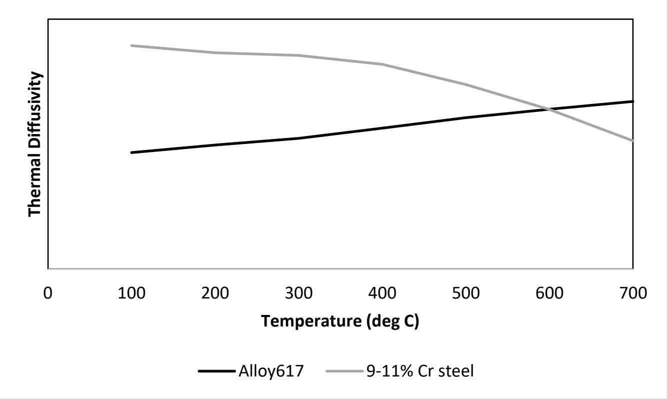

Fig. 4. Comparison of thermal diffusivity

HP/IP turbine rotors of steam turbine are subjected to creep and fatigue simultaneously. Linear Damage Accumulation (LDA) rule is used for combining creep and fatigue damages and bilinear (0.3-0.3 rule) damage interaction diagram is used for creep-fatigue interaction.[15] Tests are going on at the operating range of AUSC to generate more points for creep fatigue damage diagram, so that conservatism of the damage diagram used for design could be assured.

To get more confidence in design, component level accelerated creep-fatigue tests on actual rotor size forging pieces (segment of actual rotor) are planned to be conducted during the R&D phase. It is planned to test two such rotor segments; one monometallic Alloy617(M) piece and another one containing a dissimilar metal weld joint between Alloy617(M) and 10% Cr steel. Testing parameters and heating/cooling rate shall be raised appropriately to accelerate creep-fatigue damage to simulate expected damage in actual rotor.

V. SUMMARY

Development of AUSC power plant in a very short time is taken as a mission project by Indian consortium. Lower material properties of Alloy617(M) with respect to 10% Cr steel makes the design of an AUSC rotor more challenging.

The experience of industries on Alloy617(M) large scale forgings is relatively less and operation of such forgings in fossil power plant is not proven. A prototype rotor is planned to be manufactured as a part of technology development during R&D phase, so that the issues related to manufacturing of actual rotor can be sorted out during R&D phase. Wherever possible, efforts are being made to indigenously produce advanced materials and use them for manufacturing of AUSC turbine components. To develop confidence in overall development process; extensive material testing, prototype manufacturing and component level testing are under progress. Accelerated creep-fatigue tests of actual size rotor forging segments are also planned.

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