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Ni-based superalloys operating under challenging conditions require high mechanical strength at elevated temperatures where heat treatment processes are crucial for those materials including solutionizing and aging. The yield strength of these alloys arises concurrently from different strengthening mechanisms and the main strengthening mechanism for an alloy can change depending on the composition and processing methods. Starting from solidification, the optimu solutionizing temperature for Waspaloy is determined and isothermal aging parameters were set with ICME meth here results were compared with physical experiments. By using the modeling results, yield strength estimation onducted from roo temperature to operational temperatures and validated with thermomechanical experimen wan and coherency strengthening were each found to have a great impact on yield strength, showing the import f heat treatment processes on Waspaloy. The methods described and the model developed can be used for re composition and microstructure to have the desired strength.

KEYWORDS: WASPALOY - NI-BASED SUPERALLOY - HEAT TREATMENT - PANDAT™ - MODELING

INTROD

Ni-based s loys are designed and developed to operate un h temperatures, high mechanical loads, and corrosi ironments, in regard to the Brayton cycle where high ciency systems such as turbine engines are require o provide these challenging properties, these mate re designed by including many alloying elements f ase transformations that contribute to corrosion nce and material strength at elevated temperatur sing from solid solution hardening and grain boun trengthening of γ-matrix, precipitation hardening, coherency strengthening due to γ' particles. H eatment processes adequately designed have a grea act on overall strength with respect to the amount istribution of $L1_2$ γ' particles. Since there are many nt mechanisms contributing to overall strength, e ishing a physically based model becomes more crucial in alloy design fields due to the difficulty of investigating the contribution of each strengthening mechanism in experiments by isolating the mechanism

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which is also affected by chemical composition and phase fractions.

The coherency and solid solution strengthening contribution on overall yield strength is found to be a subject open for discussion in some studies (2-11); however, according to the authors' knowledge, coherent and semi- coherent particles' interaction with γ-matrix and strain fields occurring due to substitutional and interstitial alloying atoms create obstacles for dislocation movement and increases the material strength. Therefore, the combined effects of grain boundary, coherency, and solid solution strengthening should be considered to predict the yield strength of the material.

Although computational alloy design studies with related software give a prediction on yield strength, the results obtained in such simulations have shown overprediction where optimization of the heat treatment parameters to obtain desired properties is crucial for the design of such materials.

In this study, isothermal aging of Waspaloy is applied to model the effect of each strengthening mechanism calculated by using the thermodynamic and precipitation modeling outputs. For the validation of modeling studies, physical experiments were performed both at room temperature and around operational conditions. The model is expected to be used in alloy design in the future for the optimization of material performance with the related composition and microstructure.

METHOD

C , M , T E

To investigate the microstructural variations during heat treatment and predict the yield strength accordingly, the composition of the as-received Waspaloy was analyzed with optical emission spectroscopy (OES) from 5 different locations on diameter.

Tab.1 - Chemical composition of the as-received Waspaloy (without P and S).

Element	Al	B	C	Cr	Co	Fe	Mo	Si	Ti	Ni
Mean wt%	1.4									

Since the ingot studied was procured in hot forged condition, the microstructure of the as-received ingot was also analyzed from the same 5 locations with optical microscopy (OM) for the determination of mean grain size in accordance with ASTM E-112 and secondary electron microscopy (SEM) together with energy dispersive spectrometry (EDS) for microstructural analysis including γ', carbide size and amount determination that will affect the desired time for solutionizing. The samples were cut with electrical discharge machining (EDM) and embedded in conductive bakelite. Grinding with SiC abrasive papers and polishing with diamond suspensions were applied for surface preparation. All samples were etched with 2 gr $CuSO_4$ + 40 ml HCl + 40 ml Ethanol (95%) etchant (12).

Heat treatment applications at 1080°C for 1-hour for solutionizing followed by water quenching and aging at 850°C for 18-hours followed by water quenching were conducted with THERMNEVO – Nevola Curing Furnace on 12 mm diameter rods prepared with EDM. After solutionizing and aging, high-resolution transmission electron microscopy (HRTEM) was used for the γ' fraction and size determination. The samples cut in 0.35 mm thickness were used for the extraction of 3mm diameter discs by using a disc punch and further prepared with grinding and twin-jet electrolytic polishing with 10 vol. % perchloric acid at 20.5V at -5°C.

Aged samples were subjected to CNC machining for tensile test preparation with SMR311 geometry. Gleeble 3800 system was used for tensile testing at room temperature, 580°C, 650°C, and 720° with 10^{-3} strain rate.

S M

The PANDAT™ software with the PanNi2023_all database and chemical composition given in Table 1 were used to predict the equilibrium and Scheil solidification phase compositions and phase fractions in regard to the CALPHAD method. The thermodynamic equilibrium of a given system with multiphase equilibria at constant pressure is determined with respect to the summation of molar Gibbs energies of the stable phases, leading to minimum Gibbs energy.

(1)

Simulation Parameter	γ-matrix	γ' precipitates
Molar Volume [m^3/mole]	7.1E-6	7.1E-6
Grain Size [m]	35	-
Dislocation Density [m^{-2}]	1E-12	-
Aspect Ratio	1	1
Interfacial Energy [J/m^2]	-	0.030
Atomic Spacing [m]	-	3.621E-10
Contact Angle [°]	-	90

Langer-Sc Kampmann-Wagner approach also known as (Kampmann-Wagner Numerical model)

Where J_s is stationary nucleation rate, is incubation time,

N_0

where χ is materia[illegible]tant changing from 2 to 3, ε is the misfit strain parameter, is shear modulus of precipitates and

Although the fraction of γ' precipitates did not reflect the real heat treatment process as understood from the TEM images, the size of the γ' particles was predicted almost the same as the aging process continues. Both the simulation and TEM analysis gave similar results for γ' precipitate radius of 24.8 nm and 25.2 nm, respectively as shown in Table 4. However, although the simulation setup is prepared for homogeneous nucleation and growth, from the TEM images the nucleation characteristic is seen as semi-homogeneous in the microstructure. Lastly, although the model expected a wider LSW distribution for the radius of the particles with varying sizes, TEM analysis has shown a narrower size distribution mainly focusing on 18 to 30 nm γ' particles.

With respect to the equations described before, yield strength estimation at different temperatures is completed by using the outcomes obtained in modeling studies conducted with PANDAT™. In order to complete the yield strength predictions at elevated temperatures more accurately, some terms such as lattice strength of pure Nickel, Poisson's ratio, shear modulus, Burger's vector, lattice parameters of γ-matrix and γ' particles, interparticle spacing and parameters were calculated by using JMatPro software from room temperature to elevated temperatures and used in the yield strength modeling as a function of temperature. The model parameters used for the determination of the effect of strengthening mechanisms and overall yield strength are given in Table 5, below.

microstructural modeling results have also shown a good