# EFFECT OF GAMMA PRIME PRECIPITATE SIZE ON THE MECHANICAL PROPERTIES OF A CAST NICKEL-BASE SUPERALLOY

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## ABSTRACT

The effect of gamma prime precipitate size on the monotonic and cyclic properties of Udimet 500 were determined. Gamma prime diameters of from 500-3000 angstroms were obtained by varying cast section thickness and hence affecting cooling rates during solidification and subsequent heat treatment. It was found that the elevated temperature yield strength decreased as a function of $1/r^n$ indicating both particle shearing and looping were active as dislocation movement mechanisms. Cyclic behavior was strongly influenced by the gamma prime size. However, the optimum size was dependent on the strain range with larger particles found to be beneficial for large strain ranges and smaller particles preferred at low strain ranges. These effects are attributed to the cyclic stress-strain exponent of the two conditions.

## KEYWORDS

Nickel-base alloys, low cycle fatigue, tensile properties, gamma prime precipitates, strain range partitioning.

## INTRODUCTION

As all materials engineers realize the mechanical behavior of a material is strongly dependent on the microstructure of the alloy. In the case of precipitation hardenable nickel-base superalloys the microstructural constituent regarded as having the greatest influence is the gamma prime precipitate and in some cases the gamma double-prime precipitate. The kinetics of precipitate nucleation and growth, and hence resultant morphology of a cast nickel-base alloy such as Udimet 500, is influenced by cooling rates during solidification and subsequent heat treatments. Therefore processing techniques which produce the desired mechanical properties for a component of relatively thin cross-sectional area may not provide similar strength in a much thicker component. In general, all things being equal the gamma prime diameters will be larger for components or areas of components of thicker sections compared to those of thinner cross-sections. Under such conditions it becomes necessary when providing material properties for these alloys to also specify the heat treatment employed as well as the section thickness for which the data is relevant. This study was undertaken to quantify the effect of the gamma prime precipitate size on both the yield strength and fatigue behavior.

## TEST PROCEDURES AND RESULTS

Specimen Conditions. Specimens containing widely varying gamma prime sizes were obtained by casting components of different section thickness while maintaining all casting process variables constant. The components were then hip'd and heat treated as described below:

1. Hot Isostatic Pressing
   Temperature-1204°C
   Time-4 hours
   Pressure-103 MPa

2. Heat Treatment
   Solutioned-1149°C for 4 hours
   Stabilized-1079°C for 4 hours
   Precipitation-760°C for 16 hours

Specimens from each component were machined for tensile and fatigue testing per standard configurations. Tensile testing was conducted at 482°C and the strain controlled low cycle fatigue testing was conducted at 650°C under plastic-plastic conditions. Gamma prime precipitate sizes were determined from scanning electron microscope examination of polished metallographic specimens using image analysis equipment.

Monotonic Tensile Test Results and Discussion. When nickel-base alloys such as Udimet 500 are strained, dislocations begin to move through the material until their paths are blocked by the gamma prime precipitates. They will continue to pile up against the particles creating a buildup of internal stress which will eventually be sufficient to force a dislocation through or around the precipitate. Huether and Reppich(1978,1979), Reppich(1982) and Reppich et al.(1982) describe three regimes of dislocation-particle interaction which could occur as a function of particle size. At smaller particle sizes, the yield strength increases parabolically with increasing particle radius as described by the Brownand Ham theory. At a critical radius the particles are large enough to permit both dislocations(weak and strongly coupled) to exist simultaneously in the precipitate. This indicates a transition from weak coupling to strong coupling of dislocation pairs. Above the critical radius a hyperbolic decrease in yield strength is predicted with a further increase in particle diameter as in equation 1.

$$\Delta\tau = \alpha\left(\frac{\gamma_0 G f w}{r}\right)^{1/2} \qquad (1)$$

some still larger radius, Orowan looping becomes competitive with the shearing process and the yield strength decreases as a function of 1/r as in equation 2. Whether or not looping occurs is a function of particle geometry and volume fraction.

$$\tau_o = \tau_y + \frac{Gb}{4\pi}\phi \ln\left(\frac{\Lambda-2r}{2b}\right)\left(\frac{1}{(\Lambda-2r)/2}\right) \qquad (2)$$

Where $b$ is the burgers vector, $\Lambda$ is the interparticle spacing and $\phi$ is a constant. The results of the tensile testing are shown in Figure 1. A nonlinear curve fit was performed using a Marquardt-Levenberg algorithm. It was found that the yield strength varied approximately as $(r)^{-0.7}$ for the precipitate diameters tested. Orowan looping is expected to be the primary mechanism of dislocation movement around the particles, however the deviation from the 1/r relationship may be due to inhomogeneous gamma prime sizes in the specimens or some shearing of particles obeying equation 1.

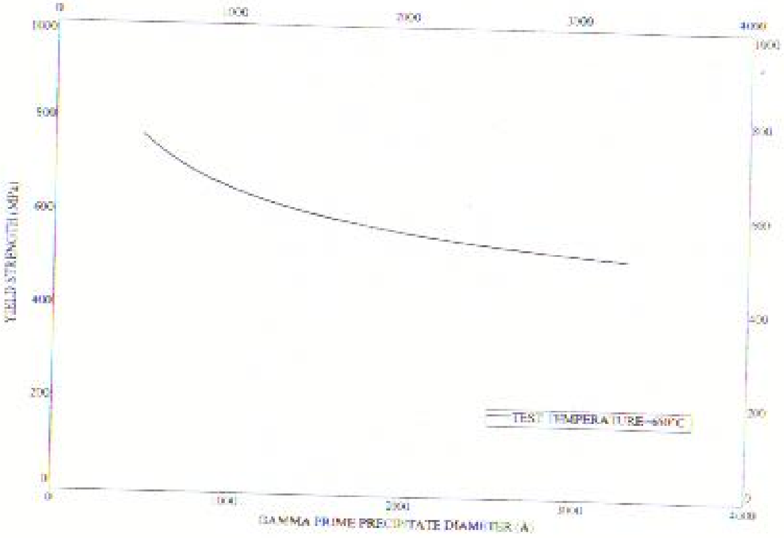

Figure 1 Results of monotonic tensile testing

Cyclic Test Results and Discussion. The effect of precipitate size on the cyclic behavior of nickel-base alloys is complicated due to the complex interactions of precipitates are their relative ability to cyclically soften or harden during testing at elevated temperatures. The general behavior has been described eloquently by Antolovich and Lerch (1989). The normalized behavior of the specimens containing the largest gamma prime precipitates relative to those containing the smallest gamma prime particles is shown in Figure 2. At low strain ranges the specimens containing the small precipitates exhibit longer lives than those with large precipitates, while the opposite is true at high strain ranges. A theory to explain

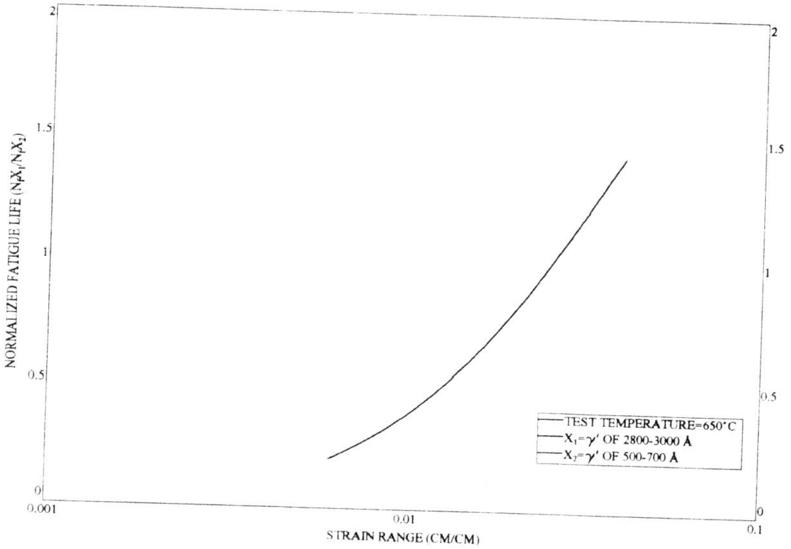

Figure 2 Results of strain controlled (plastic-plastic) fatigue testing

such behavior has been proposed by Lerch and Gerold (1987) based on the work hardening characteristics of superalloys during cyclic loading. To get an idea of the work hardening characteristics of the test specimens the maximum stress was plotted against the applied strain range in a double logarithmic fashion as shown in Figure 3. The slope of the curves (n') is referred to as the cyclic stress-strain exponent and is a measure of the amount of work hardening which occurs during fatigue. At high strain ranges the material which work hardens more rapidly results in a higher response stress which for a given strain range provides a greater driving force for crack initiation and propagation thus reducing fatigue life. At lower strain ranges the majority of the deformation occurs elastically within the grains and the dislocations in these grains in these grains are free to move back and forth across the grain, meeting with no resistance from any intersecting planes. Thus no work hardening occurs and the material having the higher tensile strength exhibits the longer life; in this study the specimens containing the smaller precipitate sizes exhibited the higher tensile strength. Stoltz and Pineau (1978) found that materials having a more homogeneous dislocation structure work hardened more rapidly. Studies on the dislocation structure of subject materials after testing was outside the scope this work.

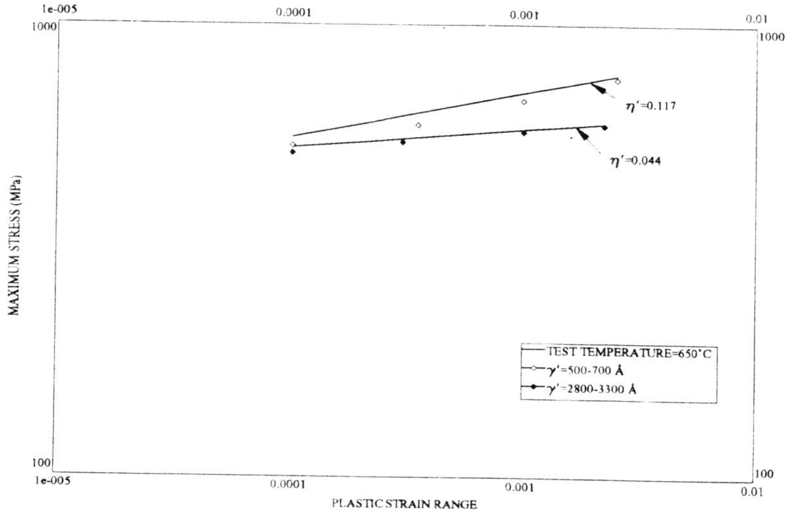

Figure 3 Work hardening characteristics of materials tested

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