MICROMECHANICS OF HIGH TEMPERATURE DEFORMATION AND FAILURE

S. Nemat-Nasser and J.R. Weertman
Northwestern University
Evanston, Illinois 60201

The aim of the current research sponsored by NASA-Lewis Research Center at Northwestern University has been to examine the micromechanics of the constitutive behavior of elasto-plastic materials at high temperatures. This research involves theoretical and experimental effort.

The experimental work has focused on the development of microscopic defects in superalloys (Waspaloy), especially the formation of voids at grain boundary carbides, and slip-induced surface cracks within grains upon cyclic loading at high temperatures. The influence of these defects on the life-expectancy of the material is being examined.

The theoretical work consists of two parts: (1) Analytical description of the mechanisms that lead to defects observed experimentally; and (2) development of macroscopic elasto-plastic nonlinear constitutive relations on the basis of micromechanical modeling.

1. PROGRESS TO DATE

A list of articles completed under the current grant is given in Section 2. Progress in experimental and theoretical efforts is briefly discussed in Subsections 1.1 and 1.2.

1.1 Experimental Effort

A study is under way of the effect of prior deformation, carried out at room temperature, on the subsequent high temperature fatigue behavior of Waspaloy.

At room temperature Waspaloy deforms by coarse, planar slip whereas by 650°C slip has become fine and homogeneous. Pineau and coworkers, Refs. [1,2], have shown that the planar low temperature behavior can be extended to higher temperatures if the material is deformed at room temperature prior to high temperature fatigue.

In the series of experiments now in progress the effect of monotonic prestrain and of prefatiguing at room temperature on samples fatigued at 650-750°C is being investigated. Samples of Waspaloy were pulled at room temperature to a strain of about 4% or were fatigued with a plastic strain amplitude of 0.3% or 0.6% at a frequency of 0.05 Hz. The specimens then were fatigued at 0.05 Hz at 650°C with a stress amplitude of 810 MPa or at 750°C with an amplitude of 770 MPa. All high temperature fatiguing was carried out in a vacuum of about 10^{-6} torr. Several samples were subjected to high temperature fatiguing which had undergone no prior deformation, in order to observe the effect of prior deformation on high temperature fatigue behavior.

Both monotonic straining and fatiguing produce coarse slip at room temperature. While some slip lines appear straight, many detour around the larger γ' particles. Shearing of γ' particles is not universal during room temperature deformation. (The distribution of sizes of the γ' particles is bimodal. The larger are about 200 nm in diameter.) An appreciable amount of microcracking was seen along coarse slip lines in the fatigued samples (Fig. 1) but no grain boundary cracking. A small number of grain boundary microcracks were found in the pulled material but no slip line cracks (Fig. 2). Waspaloy which was prestrained either in tension or fatigue and then fatigued at 650° or 750° also showed coarse slip bands, an appreciable number of which had turned into cracks. Prefatiguing seems to favor microcracking along the slip lines, while prior deformation by pulling produces more grain boundary voids and cracked boundaries

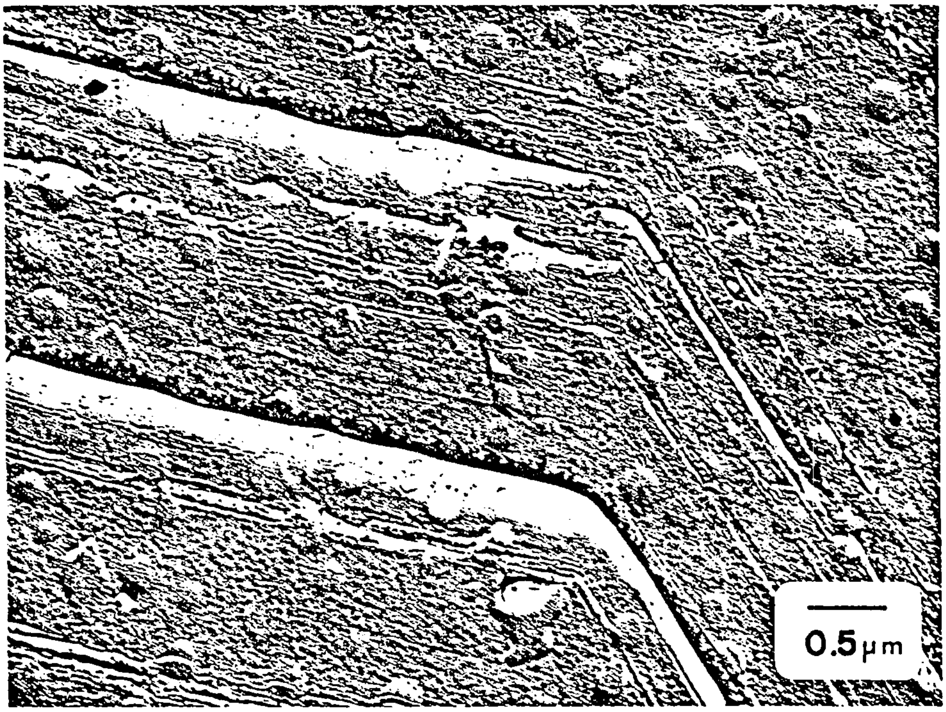

Fig. 1: TEM micrograph of a shadowed 2-stage replica of Waspaloy fatigued at room temperature for 100 cycles (0.1 N_f) at a plastic strain amplitude of 0.6% at a frequency of 0.05 Hz. Several microcracks along coarse slip lines are seen on either side of the twin boundary.

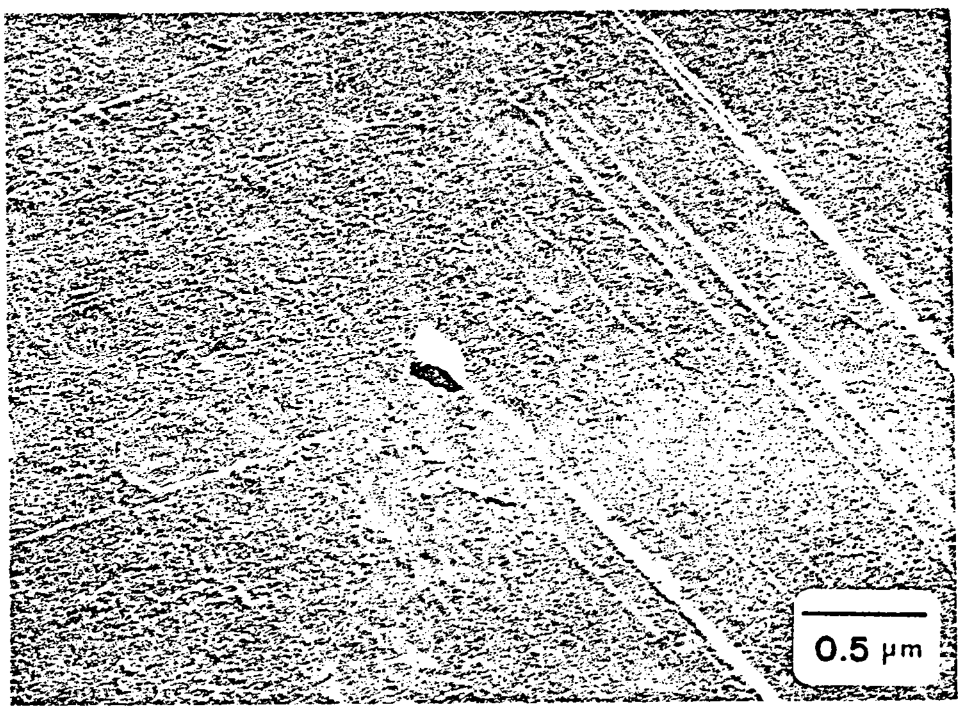

Fig. 2: Shadowed 2-stage replica of Waspaloy pulled to a 4% strain at room temperature. Note coarse slip lines, one of which ends in a microcrack at the grain boundary.

(Figs. 3 and 4). The slip generally is finer in specimens fatigued at high temperature which had not undergone prior deformation (Fig. 5). Slip line and grain boundary cracking appear only after 500 cycles in these specimens, whereas such features appear by 200 cycles in the prestrained samples.

1.2 Theoretical Effort

A complete formulation of the overall macroscopic elasto-plastic response of polycrystalline solids at finite strains and rotations has been made; Ref. [3]. A number of illustrative examples have been worked out. A number of interesting new results have been obtained. In particular, the influence of residual stresses (backstress) at the micro-level on the overall mechanical response has been thoroughly examined. In addition, based on a micromechanical modeling, the macroscopic Bauschinger effect and kinematic hardening are exemplified.

In Refs. [4,5] dynamic crack growth in elasto-plastic materials is given a complete asymptotic solution. These results shed new light on this difficult problem area and bring out a number of technically important questions pertaining to criteria for ductile fracture.

Other articles listed in Section 3 respresent various other micromechanical aspects of the research which has been completed.

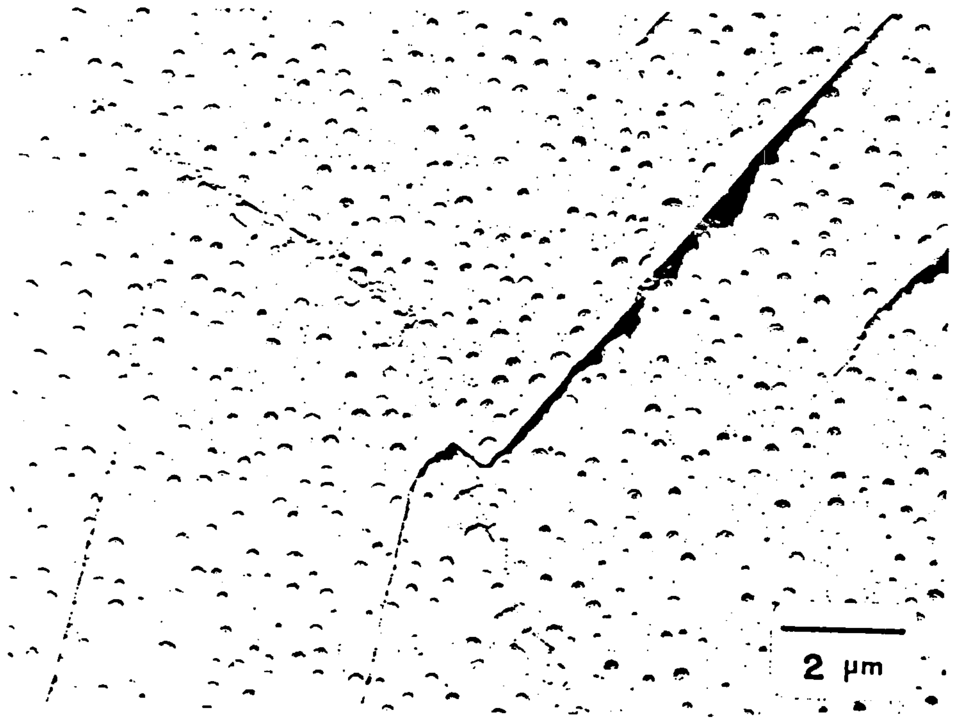

Fig. 3: Replica of a slip line crack which has jumped the grain boundary and continued on another slip system. Specimen of Waspaloy prefatigued at room temperature for 200 cycles (0.1 N_f) at a plastic strain amplitude of 0.3%, then fatigued for 160 cycles at 650°C with a stress amplitude of 810 MPa. All fatiguing done at a frequency of 0.05 Hz, and in a vacuum of $\sim 10^{-6}$ torr.

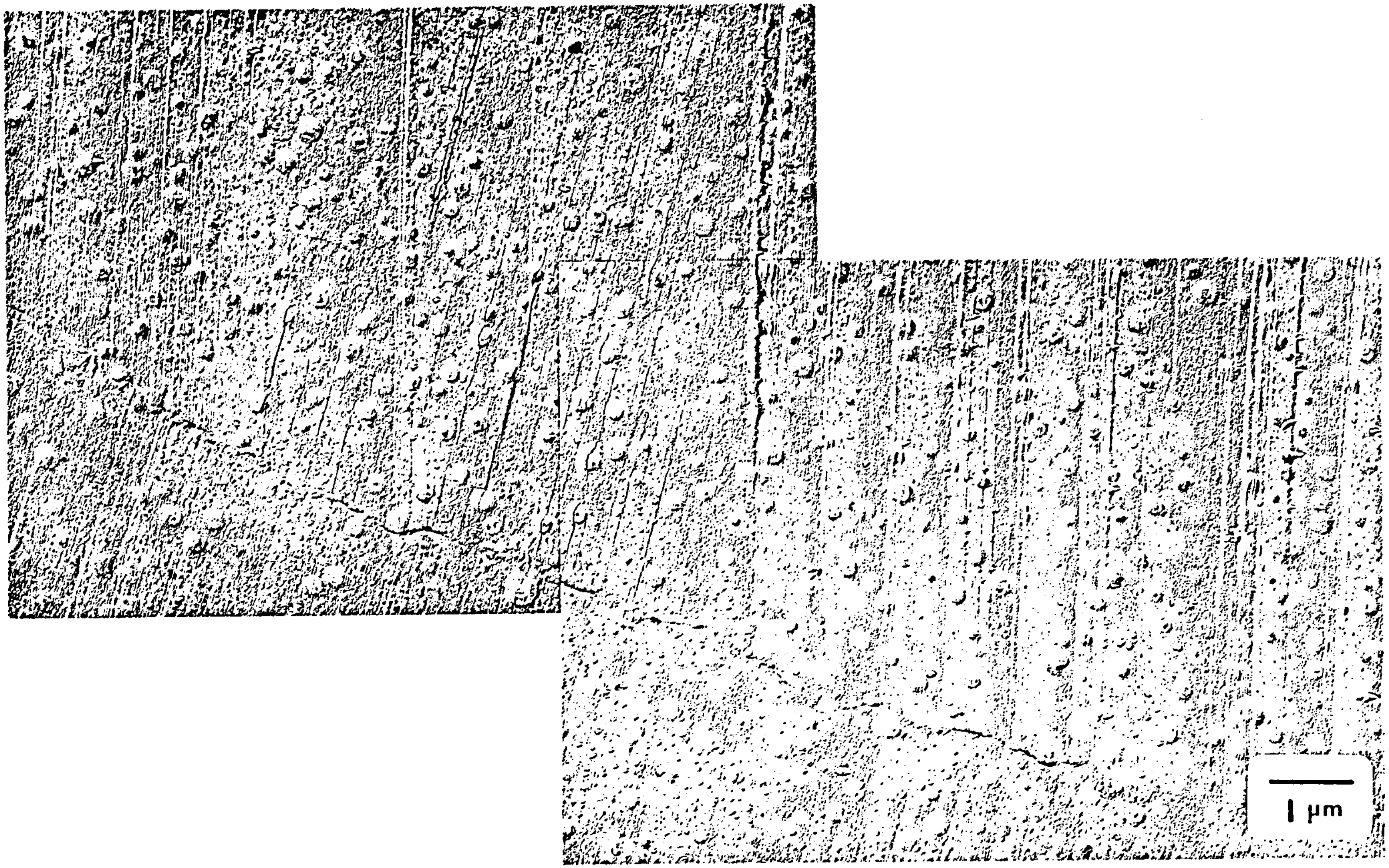

Fig. 4: Micrograph of replica of Waspaloy specimen pulled at room temperature to a 4.1% strain, then fatigued at 750°C at a frequency of 0.05 Hz with a stress amplitude of 770 MPa for 150 cycles. Note the coarse slip and the numerous microcracks along the grain boundary. A slip line crack also can be seen.

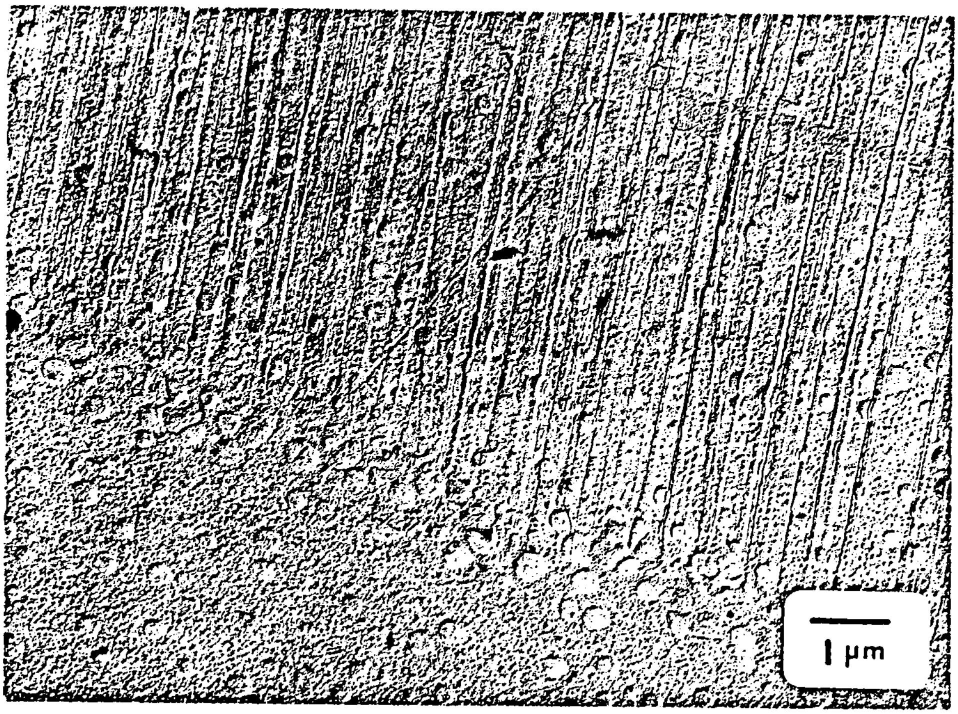

Fig. 5: Slip on a finer scale in Waspaloy fatigued for 160 cycles, 0.05 Hz, 650°C with a stress amplitude of 810 MPa. No prior deformation. Note the tendency of the slip lines to go around the large γ′ particles.

2. PUBLICATIONS

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2. S. Nemat-Nasser, "On Finite Deformation Elasto-Plasticity," International Journal of Solids and Structures, Vol. 18 (1982), pp. 857-872.

3. Y. Murakami and S. Nemat-Nasser, "Growth and Stability of Interacting Surface Flaws of Arbitrary Shape," Engineering Fracture Mechanics, Vol. 17 (1983), pp. 193-210.

4. T. Iwakuma and S. Nemat-Nasser, "Composites with Periodic Microstructure," Advances and Trends in Structural and Solid Mechanics, Proc. Symp., Washington, D.C., Oct. 4-7, 1982, A. K. Noor and J. M. Housner (eds.), Pergamon Press (1983), pp. 13-19; also in Computers and Structures, Vol. 16 (1983), pp. 13-19.

5. Y. C. Gao and S. Nemat-Nasser, "Dynamic Fields Near a Crack Tip Growing in an Elastic-Perfectly-Plastic Solid," Mechanics of Materials, Vol. 2, (1983), pp. 47-60.

6. K. Motoie, M. Sakane, and J. Schmidt, "An Extensometer for Axial Strain Measurement at High Temperature," Mechanics of Materials, Vol. 2 (1983), pp. 179-182.

7. S. Nemat-Nasser, "Recent Progress in the Description of Inelastic Behavior of Materials with Microdefects," (Invited Lecture), Transactions of the 7th International Conference on Structural Mechanics in Reactor Technology, North-Holland (1983), Vol.L, Paper L/1*, pp. 69-77.

8. T. Iwakuma and S. Nemat-Nasser, "Finite Elastic-Plastic Deformation of Polycrystalline Metals," to appear in Proc. Roy. Soc. London (1984).

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[1] M. Clavel and A. Pineau, Scripta Metall. 16 (1982), 361.

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[4] Y. C. Gao and S. Nemat-Nasser, "Dynamic Fields Near a Crack Tip Growing in an Elastic-Perfectly-Plastic Solid," Mechanics of Materials 2 (1983), 47-60.

[5] Y. C. Gao and S. Nemat-Nasser, "Mode II Dynamic Fields Near a Crack Tip Growing in an Elastic-Perfectly-Plastic Solid," J. Mech. Phys. Solids 32 (1984), 1-19.