COMPARISON OF SINGLE AND MULTIPLE PASS COMPRESSION TESTS USED TO SIMULATE MICROSTRUCTURAL EVOLUTION DURING HOT WORKING OF ALLOYS 718 AND 304L

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Abstract

Microstructural evolution during primary breakdown of alloy 718 by radial forging was studied via axial compression testing of cylindrical specimens taken from a wrought and solution heat treated bar with an average grain diameter of 254 μm. Tests were performed at a constant true strain rate of 1 s^{-1} and at temperatures of 950°C, 1050°C, and 1150°C. Total plastic strains of 0.56 and 0.92 were applied either in one pass or by four consecutive passes. The strain per pass for each four-pass sequence was either 0.14 or 0.23. Dwell periods between passes and after the final pass were utilized to simulate the deformation-time history of a typical production workpiece. The dwell time applied after compression and before the quench in the single-pass test equalled the sum of the individual dwell periods of the four-pass test (240 s). The single-pass tests were found to underestimate the grain refinement at all deformation temperatures and overestimate the volume recrystallized at the lowest temperature. The relatively fine grain size of the four-pass material is attributed to the repetitive static recrystallization that occurs during back to back dwell periods. Softening in the stress-strain curve at high strain and extensive static recrystallization following deformation of single-pass material, deformed at 950°C, was observed and attributed to deformational heating (approx. 60°C). Deformational heating and its effects were moderated during the four-pass tests by heat dissipation during the dwell periods (70 s) between passes. Alloy 304L was also tested and its behavior was found to be generally similar to that of alloy 718 at or above 1050°C. It is concluded that the multiple-pass compression test provides a better technique for simulating microstructural evolution during primary breakdown of ingot material by radial forging.

Superalloys 718, 625, 706 and Various Derivatives
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Background

The hot deformation behavior and microstructural response of alloy 718 has been the subject of various research programs conducted over the past ten years at the Advanced Steel Processing and Products Research Center at the Colorado School of Mines, Golden, Colorado. The initial series of studies (1-4) utilized single-pass isothermal compression testing to examine the dynamic stress-strain (σ-ϵ) response and recrystallization behavior of as-cast alloy 718. Variations in the ingot structure from position to position were shown to have a significant effect on the flow stress (σ_f) the shape of the σ-ϵ curve, and the deformed sample geometry. Recrystallization behavior, however, was not greatly affected by variations in ingot structure and position. Recrystallization was found to occur after (statically), rather than during (dynamically), the imposed deformation. Subsequent studies utilized multiple-pass deformation sequences to study microstructural evolution during radial forging (5), a common technique for ingot break-down and the production of intermediate size bar, and during ring rolling (6,7). In the radial forging study (5), alloy 718 recrystallized during the dwell time between each deformation pass with the extent of recrystallization depending in part on temperature, strain, hold time, and instantaneous grain size. It was concluded that repeated recrystallization between passes can be employed to produce fine grain intermediate size bar from coarse grain ingot via radial forging.

Introduction

The production of a uniform microstructure throughout a work piece is a desired requirement of thermo-mechanical processing schemes for alloys used in critical applications or demanding service conditions. However, hot working of even the simplest shapes, such as the reduction of ingot to bar or plate, can produce widely differing microstructures from position to position because of gradients in temperature, strain, and strain rate which inevitably arise in the work piece during processing. A detailed knowledge of the variations of these critical parameters in the workpiece, coupled with a constitutive understanding of their effect on recrystallization, recovery, and grain growth, are needed in order to develop successful processing schemes. The former can be determined via large strain finite element analysis of the process and the latter by laboratory deformation studies.

Radial or rotary forging is often used in the initial break down of production size alloy 718 ingots. Typically, deformation is applied over a falling temperature range from approximately 1150°C to as low as 800°C. The work piece velocity through the forging dies (2-5 m/min.) coupled with the imposed reduction in cross section area (10-50 percent) results in a typical strain rate of approximately 1 s^{-1}. During radial forging, the ingot is worked first in one direction through the dies and then the other. Figure 1 is a schematic of a typical deformation dwell time history for a 2.5 m long ingot traveling at 2.5 m/min. As shown, the deformation-dwell time history is different for each location along the length of the work piece. In a previous study (5), which utilized four-pass hot compression tests to simulate the history in Figure 1, it was demonstrated that final microstructure was dependent on the deformation-dwell time history and could be expected to vary significantly along the production work piece.

Multiple-pass testing to simulate microstructural evolution during primary breakdown via radial forging requires extensive laboratory development and may not be possible on some existing mechanical testing equipment that is capable of single-pass compression testing. Comparison of microstructures produced by single-pass and multiple-pass sequences is needed to discern the benefits of multiple-pass testing in such simulation experiments. The purpose of this investigation was to characterize the evolution of microstructure during single-pass compression testing and compare the results to those obtained from multiple-pass testing (5) to determine if multiple-pass compression testing can be reduced to single-pass testing. In both studies, the starting material, deformation temperatures, total applied strains, and total dwell time were identical. Values of final recrystallized grain size (D_{rex}) and volume percent recrystallized (V_{rex}) are used to compare the final microstructures produced by the two deformation techniques, single-pass and four-pass compression testing.

Experimental Procedure

The alloy 718 material utilized in the prior investigation (5) and in this investigation, provided by Carpenter Technology Corporation, was vacuum induction melted followed by vacuum arc remelting into a 406 mm diameter cylindrical ingot. The chemistry of the alloy is given in Table I. The ingot was homogenized, and then radial forged and rolled to 16.5 mm diameter bar. The bar was solution heat treated at 1250°C for 7.5 hours and water quenched to simulate the coarse grain microstructure typically found in billet material during primary breakdown. Figure 2 shows the solution treated microstructure which has an average grain diameter of approximately 250 μm.

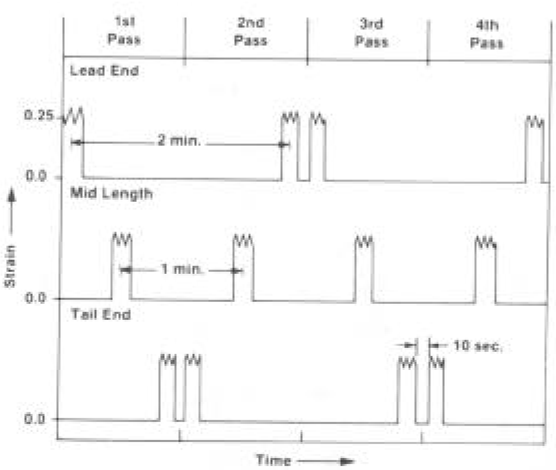

Figure 1 - Predicted deformation-dwell time histories for three different positions along the length of a work piece processed via radial forging and for a cycle time of one minute per pass.

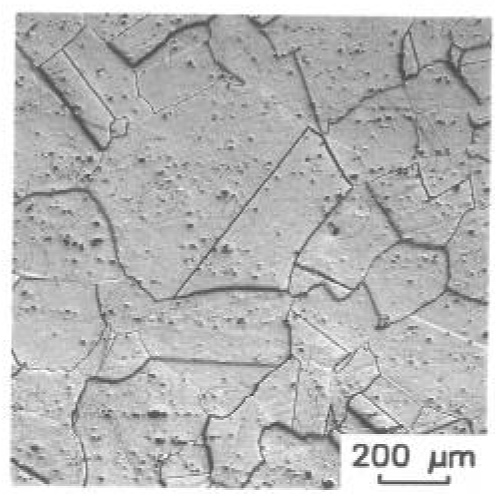

Figure 2 - Microstructure of wrought alloy 718 after 7.5 hours at 1250°C. Starting microstructure for four-pass and single-pass compression tests. Kalling's etch.

Table I - Chemical Composition of Alloy 718 and 304L Studied in this Investigation (In Mass Percent)

Element	Ni	Fe	Cr	Nb	Mo	Ti	Al	Co	Si	Mn
718	Bal.	18.99	18.32	5.18	3.05	0.98	0.55	0.35	0.21	0.12
304L	10.0	Bal.	18.6	---	0.055	---	---	0.077	0.57	1.9

Element	C	P	B	S	Cu	N
718	0.044	0.009	0.0043	0.002	0.06	---
304L	0.022	0.011	---	0.0003	---	0.015

Cylindrical compression specimens (2) were machined from the wrought and heat treated bar. Compression testing was conducted in an electric-resistance furnace between flat SiN dies. Prior to compression, the test sample, furnace atmosphere, and dies were equilibrated at the deformation temperature (T). Specimens were deformed at a constant true strain rate of 1 s^{-1}, at temperatures of 950°C, 1050°C, and 1150°C, to a total true ϵ of either 0.56 or 0.92. These values of total ϵ are consistent with the sum of the strains applied during the four-pass sequences of the earlier study (5), where the ϵ increment per pass was either 0.14 or 0.23. In the earlier study the dwell time at T was varied to simulate the actual dwell time history for various positions along the work piece. The history for the midlength position was chosen for this study. For a four-pass sequence, assuming a 1 min. cycle time through the radial forging dies coupled with a 10 s period for the workpiece to be reversed and fed back into the radial forging dies, the dwell history is 70 s + 70 s + 70 s + 30 s (Table III in reference 5). In this investigation, each single-pass test sample was held in the furnace at T after cessation of deformation for 240 s, matching the total hold time applied during four-pass tests. The samples were then quenched in water. Alloy 304L, a candidate surrogate material for alloy 718 in hot working experiments (5), was similarly tested. The chemistry of the 304L alloy is provided in Table I.

Results and Discussion

Stress-Strain Behavior

Figures 3, 4, and 5 show typical four-pass σ-ϵ curves for alloy 718, obtained previously (5), for deformation temperatures of 950°C, 1050°C, and 1150°C, respectively, and a total applied ϵ of 0.56. Also shown are the results of the corresponding single-pass tests (triangular symbols in figures) from this investigation. Figure 3 shows that at 950°C significant softening occurs during the single-pass test, beginning at a ϵ of approximately 0.2, compared to the four-pass test. In this case, softening is probably due to an increase in test sample temperature via deformational heating, which was measured in a separate study (2) to be approximately 60°C for a single-pass ϵ of 1. Assuming that the magnitude of deformational heating is linearly proportional to ϵ, the amount of heating after a single-pass ϵ of 0.56 is estimated to be 34°C. The reduction in σ_f from heating can be approximated by the variation in σ_f

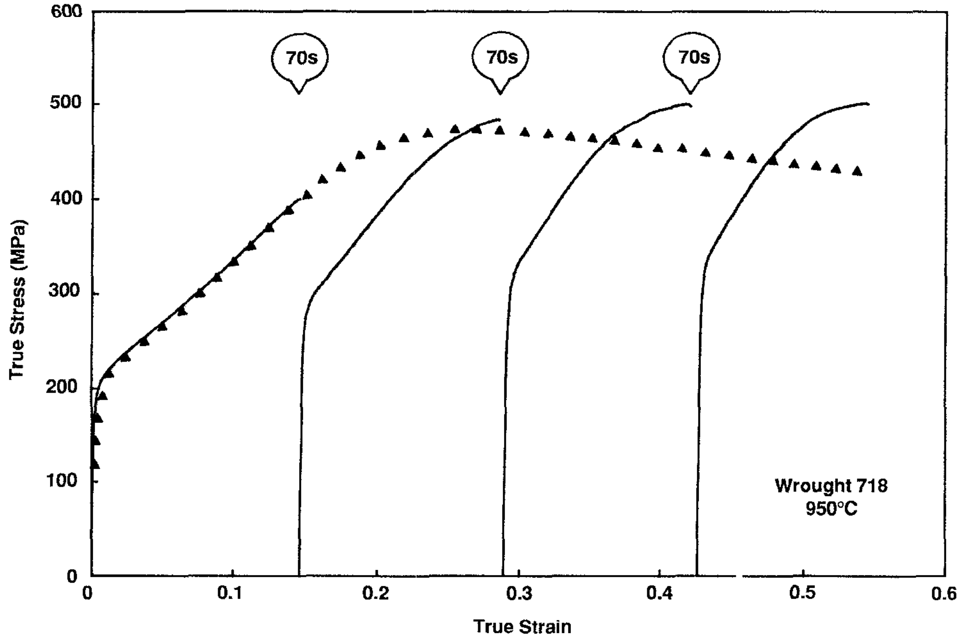

Figure 3 - True stress-true strain curves of wrought 254 μm grain diameter alloy 718 deformed at 950°C to a total strain of 0.56 in four-passes (solid curves) and in a single-pass (triangular symbols).

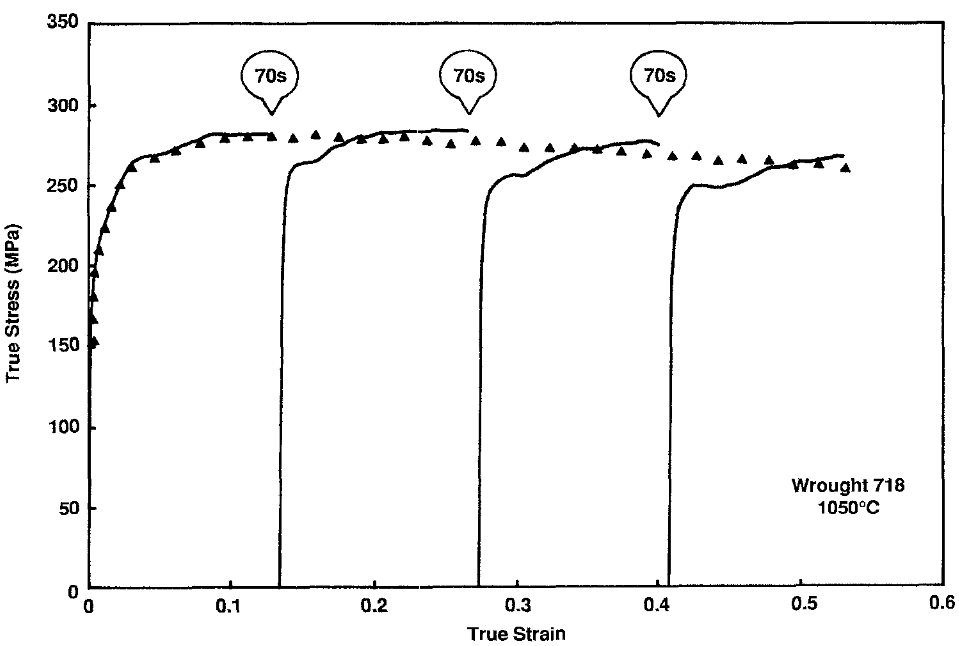

Figure 4 - True stress-true strain curves of wrought 254 μm grain diameter alloy 718 deformed at 1050°C to a total strain of 0.56 in four-passes (solid curves) and in a single-pass (triangular symbols).

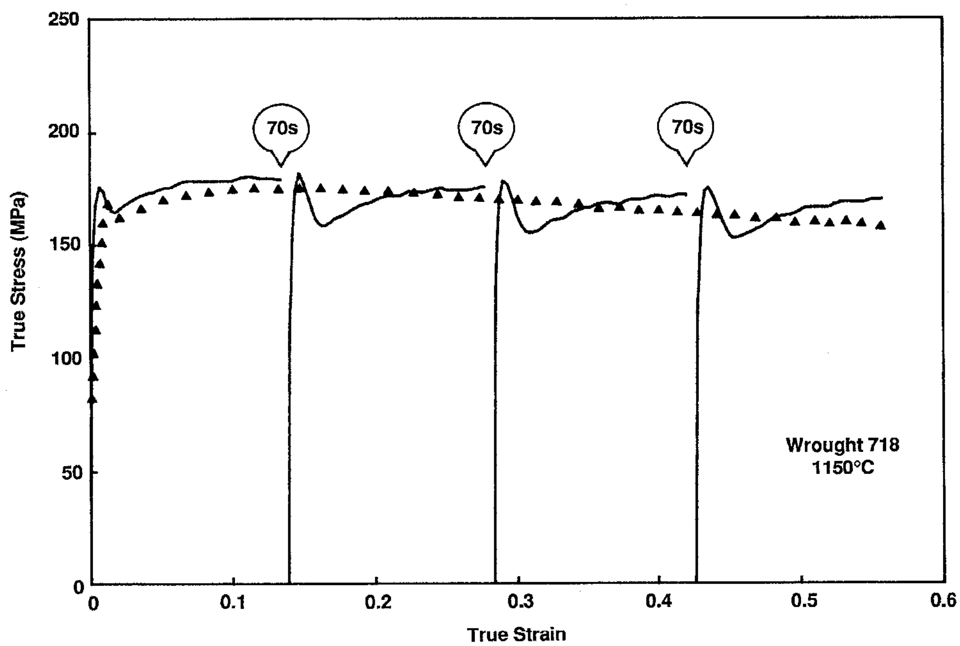

Figure 5 - True stress-true strain curves of wrought 254 μm grain diameter alloy 718 deformed at 1150°C to a total strain of 0.56 in four-passes (solid curves) and in a single-pass (triangular symbols).

with temperature obtained from the three four-pass σ-ϵ curves (Figures 3-5), assumed to represent the isothermal behavior because of the periodic 70 s dwell time which facilitates dissipation of the heat of deformation during the test. Comparing the four-pass curves, an increase in temperature from 950°C (Figure 3) to 1050°C (Figure 4) causes alloy 718 to soften by about 225 MPa, from approximately 500 MPa at 950°C to 275 MPa at 1050°C, at a ϵ of 0.56. Thus, a 34°C increase due to deformational heating during the single-pass test at 950°C would be expected to result in a softening increment of about 76 MPa at ϵ=0.56, assuming a linear variation of σ_f with T, which is consistent with the difference in σ_f (approximately 75 MPa) between the single-pass and four-pass curves in Figure 3.

At 1050°C and 1150°C, Figures 4 and 5, the single-pass and four-pass σ-ϵ curves are nearly identical with respect to the σ_f levels achieved, except for the transient behavior encountered at low ϵ upon re-loading during the four-pass tests. At 1050°C, static recrystallization causes a loss of strength during the dwell periods. Upon reloading, however, the softening is not permanent and the four-pass curves approach the σ_f level of the single-pass curve after a small amount of additional ϵ, e.g. 0.05, is applied. At 1150°C, aging during each dwell period provides a strengthening effect, characterized by the development of an upper and lower yield point. The hardening during the 1150°C dwell masks the softening from static recrystallization. Like the softening from the 1050°C dwells, hardening at 1150°C does not appear to be permanent.

Figures 6 and 7 show the corresponding σ-ϵ behavior for 304L tested at 950°C and 1150°C. Similar to 718, the single-pass and four-pass flow curves are essentially identical. One exception occurs at 950°C where the single-pass curve for 304L, Figure 6, does not exhibit softening at high ϵ relative to the corresponding four-pass curve as was observed for alloy 718 at this T, Figure 3. The difference can be attributed to the extensive static recrystallization that occurs in alloy 304L, but not in alloy 718, during the second and third dwell periods of the four-pass test (Table VI in reference 5) which results in significant and relatively permanent reduction in the average σ_f during the last two passes on 304L. Because the single-pass and four-pass curves are similar in this case, the degree of softening from deformational heating in the former must be roughly equivalent to that from static recrystallization in the latter. Softening due to dynamic recrystallization in this T, ϵ, and strain rate regime is not expected for either alloy (4,8).

Microstructural Results

Table II gives the measured values of D_{rex} and V_{rex} and Figures 8-10 show example microstructures of both the single-pass and the four-pass alloy 718 material. For the lowest T, 950°C, the two different test methods produced approximately the same D_{rex} (7-10 μm), however the single-pass method resulted in a greater V_{rex} than the corresponding four-pass method, 7 pct versus <1 pct after 0.56 ϵ and 30 pct versus 6 pct after 0.92 ϵ (Figure 8), respectively. A similar comparative behavior is also observed after testing at 1050°C (Table II). Increased recrystallization in single-pass material is attributed at least in part to higher sample temperature after deformation, due to deformational heating, which favors static recrystallization, the dominant recrystallization mechanism for the deformation history applied in this study (3-5,8). Increased recrystallization in single-pass material may also be due in part to the extensive deformation that is applied without chance for static recovery of the unrecrystallized portion of the microstructure. Greater retained work, in the form of a dense dislocation substructure, in the unrecrystallized matrix would favor static recrystallization during the 240 s hold. In comparison, static recovery of the unrecrystallized matrix, assumed to occur to some degree during the dwell periods of four-pass tests, would reduce the driving force for recrystallization in these areas (9).

At 1050°C, D_{rex} in single-pass material is significantly larger than four-pass material, e.g. 41 μm versus 22 μm from Table II, respectively, after 0.56 ϵ. This is also the case for higher ϵ, 0.92 (Figure 9), and T, 1150°C (Figure 10). At these two temperatures grain size differences between the two testing techniques are probably due to a number of other factors besides deformational heating. Single-pass curves for the two higher deformation temperatures do not exhibit much softening, Figs. 4 and 5, indicating that deformational heating was minimal. The temperature rise in the single-pass test after 0.56 ϵ is estimated, assuming heating is linearly proportional to σ_f, to be 17°C at 1050°C and 11°C at 1150°C. However, it was observed in the previous study (5) that static recrystallization did occur between passes at both 1050°C and 1150°C and that material that recrystallized during a dwell period tended to statically recrystallize again (or re-recrystallize) during the dwell period following the subsequent pass. The microstructural changes that took place during this sequence is shown in Figs. 12 and 13 of reference 5. Repeated recrystallization during successive dwell periods appears to have a substantial grain refinement effect considering that

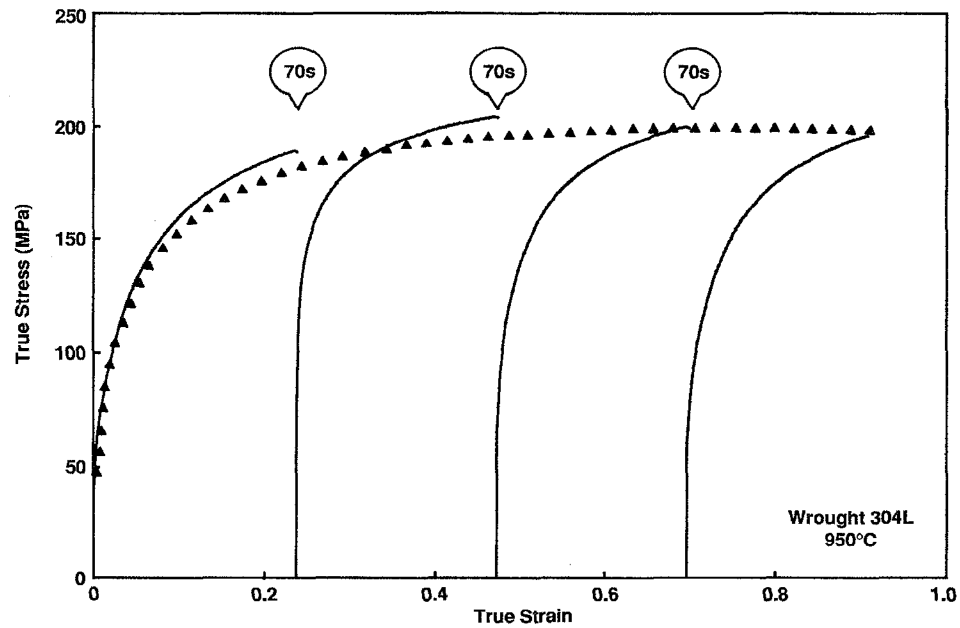

Figure 6 - True stress-true strain curves of wrought 250 μm grain diameter alloy 304L deformed at 950°C to a total strain of 0.92 in four-passes (solid curves) and in a single-pass (triangular symbols).

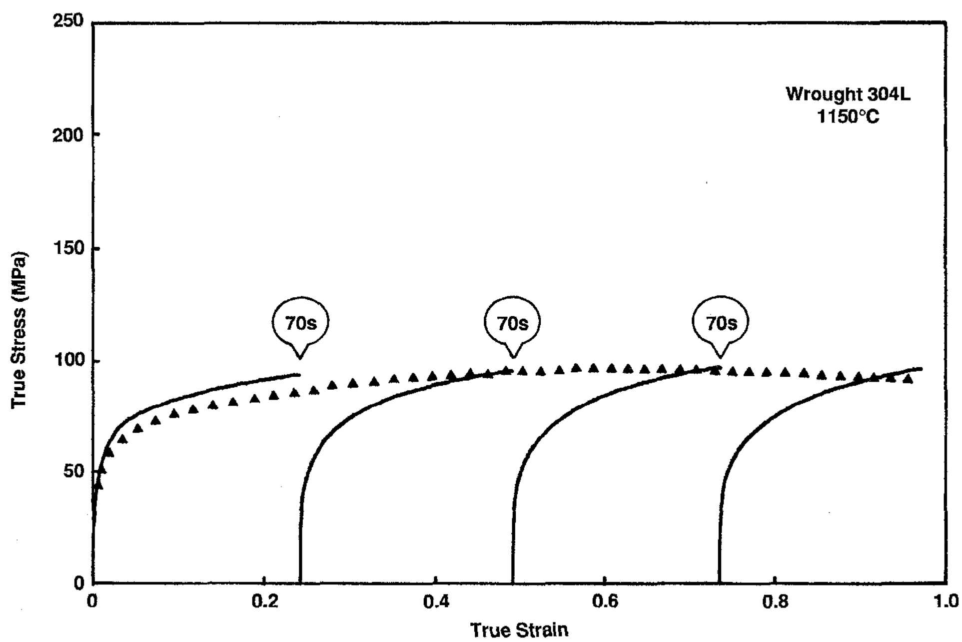

Figure 7 - True stress-true strain curves of wrought 250 μm grain diameter alloy 304L deformed at 1150°C to a total strain of 0.92 in four-passes (solid curves) and in a single-pass (triangular symbols).

Table II - Comparison of Recrystallized Grain Size, D_{rex} (μm), and Volume Percent Recrystallized (V_{rex}) Between Single-Pass and Four-Pass Compression Tests of Alloy 718 with an Initial Average Grain Diameter of 254 μm

		D_{rex}		V_{rex}	
Deformation Temperature (°C)	Strain	1-Pass	4-Pass	1-Pass	4-Pass
950°C	0.56 0.92	9 10	9 7	7 30	<1 6
1050°C	0.56 0.92	41 37	22 19	100 100	89 96
1150°C	0.56 0.92	114 98	50 50	100 100	100 100

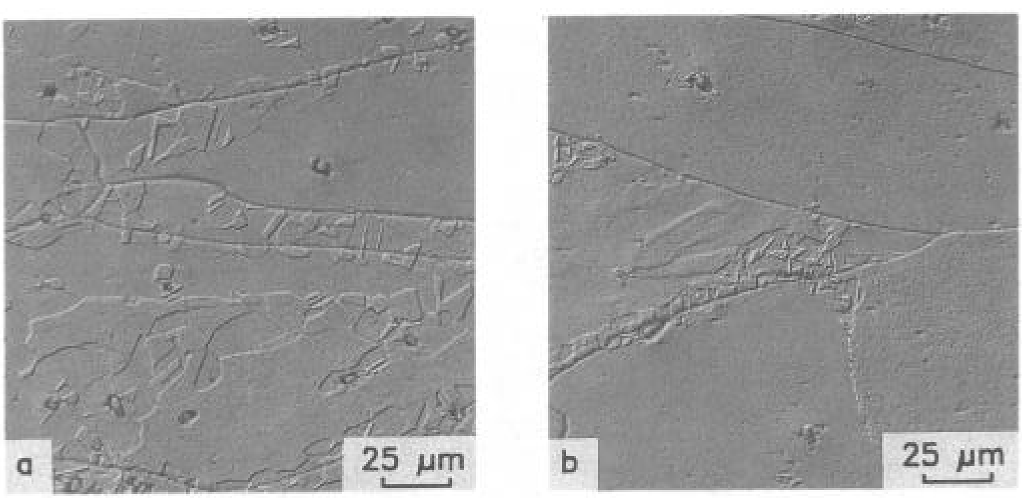

Figure 8 - Microstructure of alloy 718 deformed at 950°C to a strain of 0.92 via the (a) single-pass and (b) four-pass compression tests.

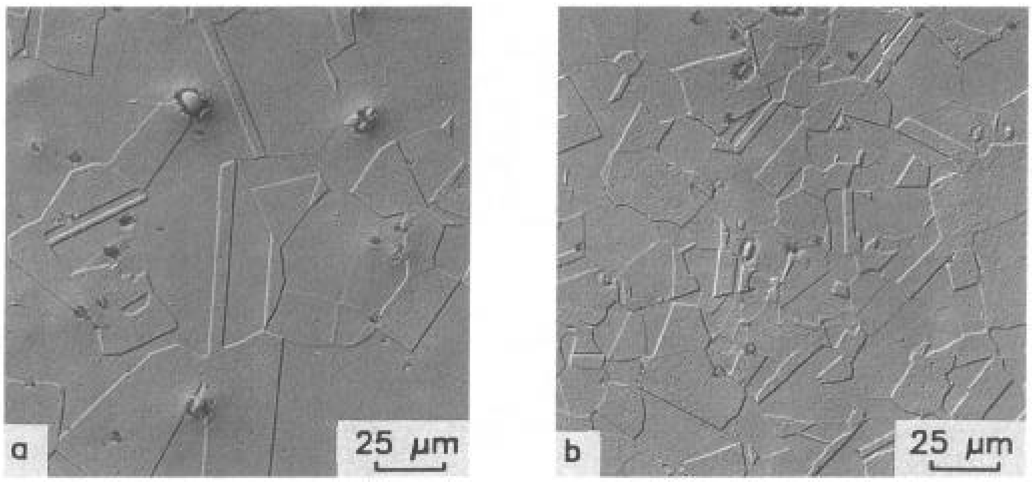

Figure 9 - Microstructure of alloy 718 deformed at 1050°C to a strain of 0.92 via (a) single-pass and (b) four-pass compression tests.

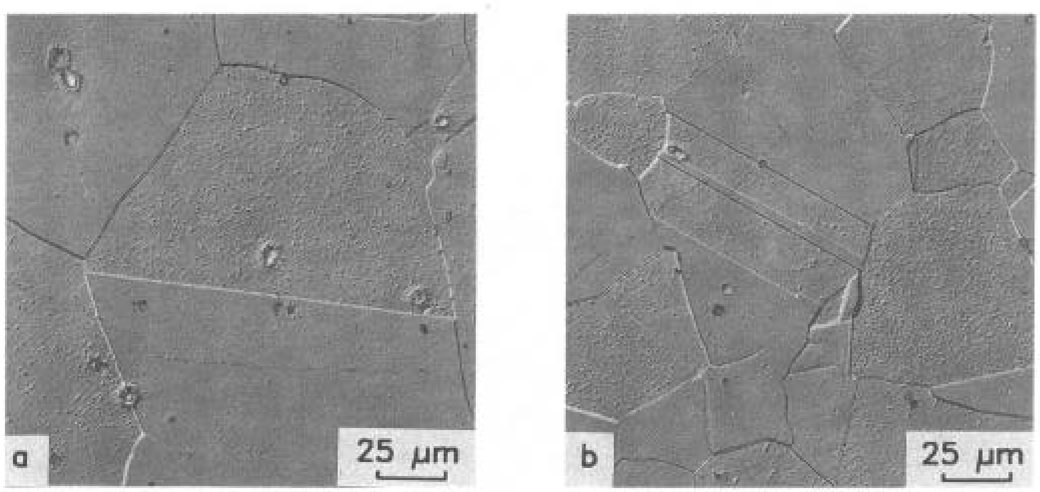

Figure 10 - Microstructure of alloy 718 deformed at 1150°C to a strain of 0.56 via (a) single-pass and (b) four-pass compression tests.

the low ϵ applied during each pass of the four-pass schedule, i.e. either 0.14 or 0.23, would favor a coarser D_{rex} compared to the high ϵ applied during the single-pass tests, i.e. either 0.56 or 0.92, which would favor a finer D_{rex}. A factor favoring coarser D_{rex} in single-pass material is the long uninterrupted dwell time, at T, after deformation which allows for grain growth following recrystallization.

Table III compares the microstructures of alloy 304L after single-pass and four-pass compression testing. Discrepancies between the values of D_{rex} and V_{rex} in material produced by the two test methods are observed and are qualitatively similar to those described for alloy 718 (Table II). Values of D_{rex} for single-pass 304L material are about twice those for four-pass material. In addition, single-pass material exhibits a significantly higher V_{rex} at low T, 950°C. Comparison of the two alloys at T=950°C shows that for equivalent deformation conditions recrystallization and grain growth are apparently more sluggish in alloy 718. For example, after a ϵ of 0.92 both the single-pass and four-pass alloy 718 samples have much lower values of V_{rex} than the corresponding 304L samples, 30 pct versus 99 pct (single-pass) and 6 pct versus 75 pct (four-pass), respectively. The corresponding recrystallized grain sizes are 10 μm versus 34 μm (single-pass) and 7 μm versus 22 μm (four-pass). The distinct difference in behavior of the two materials at 950°C is moderated at higher T. For example, at 1150°C, values for V_{rex} and D_{rex} are similar for the two alloys. The differences in behavior at T=950°C may be due to the presence of fine particles in alloy 718 which are not present in 304L (1,5,8). Thus, at high T (T>1050°C) it appears that 304L could be employed as a surrogate material for modeling the microstructural behavior of alloy 718 during hot work processing.

Table III - Comparison of Recrystallized Grain Size, D_{rex} (μm), and Volume Percent Recrystallized, V_{rex}, Between Single-Pass and Four-Pass Compression Tests of Alloy 304L with an Initial Average Grain Diameter of 250 μm

		D_{rex}		D_{rex}	
Deformation Temperature (°C)	Strain	1-Pass	4-Pass	1-Pass	4-Pass
950°C	0.56	45	27	--	20
	0.92	34	22	99	75
1050°C	0.56	74	43	100	95
	0.92	68	39	100	100
1150°C	0.56	130	66	100	100
	0.92	116	52	100	100

Summary

Microstructures and σ-ϵ curves from single-pass and four-pass compression tests were compared to assess the presumed benefit of closely duplicating the deformation-dwell time history of primary breakdown by radial forging with a multiple-pass test. The σ-ϵ behaviors measured by the two techniques are remarkably similar. Thus, from the σ-ϵ curves alone, little difference between the final microstructures of the single-pass and four-pass materials would be anticipated. However, significant differences were in fact observed. The single-pass test technique led to an underestimation of the degree of grain refinement achieved by multiple-pass deformation. Grain refinement in multiple-pass tests was due to repetitive static recrystallization during the back to back dwell periods of the test. In addition, at lower T where workpiece σ_f is high, significant deformational heating occurs during the single-pass test, accounting for, in part, the higher measured values of V_{rex} in this material compared to four-pass material. Also, the longer uninterrupted dwell time at the conclusion of the single-pass test provides significant opportunity for recrystallization and grain growth following recrystallization. It is concluded that multiple-pass tests provide better simulations than single-pass tests for the study of microstructural evolution during multiple-pass hot working schemes such as primary breakdown of ingot material via radial forging.

Acknowledgements

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