PROGRESS TOWARD A DEFORMATION MAP

FOR FINE GRAIN ALLOY 718 BILLET

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Abstract

A deformation map, or microstructural map, has been developed for Alloy 718. This map defines microstructures that are obtained as a function of temperature, strain rate, and strain when forging fine grain Alloy 718 billet. The map delineates regions of different microstructural features such as uniform grain structures resulting from dynamic recrystallization, necklace grain structures resulting from dynamic recrystallation occurring only at grain boundaries present when deformation commences, and shear bands resulting from flow localization.

The microstructural data used in the map were obtained by analysis of compression specimens. The compression testing procedures are described and some issues related to the conduct of testing are discussed. For example, details of the microstructural map obtained are sensitive to test parameters such as time at temperature before deformation, lubrication, cooling rate after testing, and of course, billet chemistry and starting microstructure. The utility of the map in forge process design is discussed.

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Introduction

Process modeling of a hot working operation such as forging is a powerful tool that promises to enhance the decision making capabilities of the forge designer, the development metallurgist, the project manager, the quality assurance team, and the component life management team. Skills from a number of disciplines, including continuum mechanics, mathematics, materials science, and computer science, are required to successfully implement process modeling. One of the requirements for forge process modeling is a knowledge of the alloy flow behavior. The flow data can also be used to develop deformation maps for an alloy. Recently, Gegel and coworkers (1) have developed a methodology for defining deformation maps that delineate safe and non-safe hot working conditions. These maps show, in processing space (that is, on axes of temperature and strain rate) the processing conditions for stable and unstable deformation and for maximum "efficiency". Stability and efficiency are determined by evaluation of parameters derived from flow data. The methodology is of tremendous value when dealing with new and difficult-to-work materials. For example, the optimum processing window for extrusion of a composite of glass and SiC whiskers was successfully determined using this approach (2). However, for an alloy like Alloy 718, which has good workability and which is required by customer specifications to be processed to achieve one of many possible microstructures, deformation maps must include a definition of resulting microstructures such as as-forged grain size. Definition of stable and efficient processing may be secondary. This paper reports the status of an effort to add microstructure, particularly grain size of Alloy 718, to process maps and to the alloy data base available to the decision making team.

Experimental Details

Material

Although Alloy 718 has an allowable range of columbium content of 5.0 to 5.5 weight percent, current strength requirements usually lead vendors to melt Alloy 718 with the columbium content at the high end of the range, i.e., 5.25 to 5.5%. For this study, material from Allvac heat #E584 with a chemistry listed in Table I was used. The heat was melted as 20" diameter VIM-VAR and cogged to 8" diameter billet. The

Table I. Alloy 718 Billet Chemistry in Weight Percent

Ni	52.76	Ti	0.93
Fe	18.34	Al	0.50
Cr	17.77	C	0.036
Cb+Ta	5.44	S	0.001
Mo	2.90	Mg	0.0016

billet was selected because it exhibited superior uniformity of microstructure, Figure 1. The grain size in most of the billet was a uniform ASTM 6.5 - 7 with no residual unrecrystallized grains. Some coarser grains existed at the surface of the billet, but this material was not used for testing. Figure 1 also shows that the extent of carbide stringering is relatively small and that, during the air cool after cogging, some delta phase precipitated at grain and twin boundaries. There is also some slight banding of spheroidized delta and/or γ'' within grains.

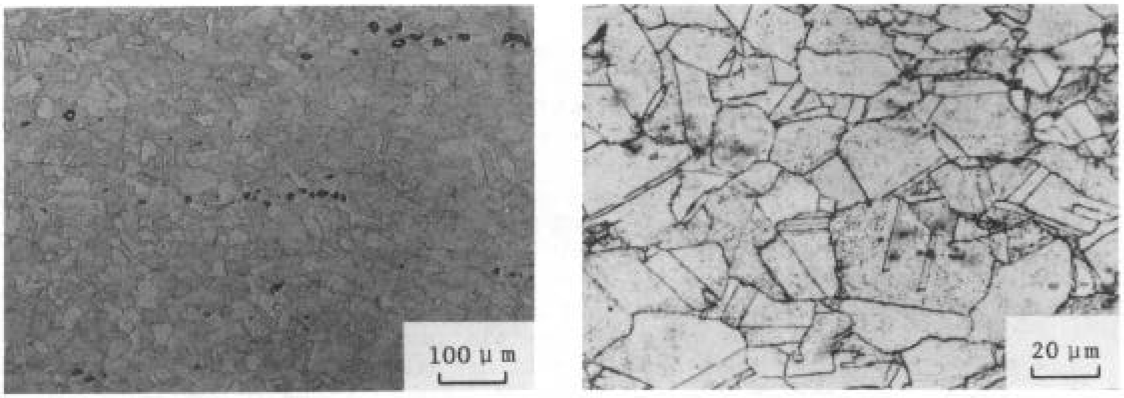


Figure 1 - As-received Alloy 718 billet microstructure.

Compression Testing

This program was an initial step in an effort to develop deformation maps for aerospace alloys, and the selections of test conditions were rather arbitrary. Ideally, data covering the whole range of possible conditions that a workpiece could experience during forging should be measured. For this study, the test temperatures varied between 1600°F (871°C) and 2000°F (1093°C) in 50°F (28°C) increments. Most normal closed die forging of Alloy 718 is carried out below 2000°F (1093°C) and, while surface workpiece metal temperatures may fall below 1600°F (871°C) because of die chilling, it is expected that metal flow in workpiece material affected by die chill will be small relative to metal flow in workpiece areas unaffected by die chill.

For strain rates, it is necessary to characterize flow behavior from strain rates characteristic of hydraulic press forging to strain rates characteristic of hammer forging because both types of equipment are used to forge Alloy 718. In this study, strain rates of 10^{-3} sec^{-1} to 10 sec^{-1} were used. The lower limit is characteristic of hydraulic press isothermal forging, which is now used only occasionally for Alloy 718. However, slow strain rates may be encountered in nonisothermal forging in some parts or all of a workpiece as a result of die geometry, die chill, or at the end of a forge stroke when the press may dwell at a prescribed load or approach the tonnage capacity of the equipment. The higher strain rate limit was imposed by the test equipment. Flow data at strain rates 10 to 100 times greater than 10 sec^{-1} are needed to characterize hammer forging.

Two different size test specimens were utilized, partly due to equipment limitations. At lower test temperatures where flow stresses were higher, specimens 0.25"Ø x 0.375" were used. These specimens were upset to a thickness of 0.145" which represents an axial true strain of 0.95. At higher test temperatures, specimens 0.4"Ø x 0.6" were employed. These specimens were deformed to a thickness of 0.285" which is an axial true strain of 0.74. Some additional 0.25"Ø x 0.375" specimens were subsequently upset to an axial true strain of 0.60.

Testing was carried out on a 20 Kip MTS direct hydraulic drive test machine. Specimens were induction heated which brought the specimens to temperature in 3 to 6 minutes, and then the samples were soaked at temperature for 10 minutes before testing. The data recorded were loads and displacements as a function of time, and these were converted to true stress vs. true plastic strain. Specimens were quenched quickly after testing to retain the dynamic microstructure as much as possible, but the times between the end of the test and the quench varied.

At this time there is no ASTM standard for the conduct of this test. The possible variables such as specimen geometry, time at temperature before testing, time between the end of the test and quenching, cooling rate, etc., vary in different testing efforts. Time at temperature before deformation for a forging is desired to be a minimum for metallurgical and economic reasons. However, the minimum possible time is often exceeded due to conservatism, scheduling, or equipment delays. Furthermore, many forging preform shapes vary in cross section and so time at temperature will vary for different locations within a single forging multiple. Ten minutes at temperature before testing represents a minimum value. With respect to quenching after deformation, quenching rapidly is desirable to retain the dynamic microstructure as much as possible. Actual forgings cool much more slowly than compression specimens because of slower handling and larger cross sections. A controlled, reproducible, relatively slow cooling rate after compression testing is probably more desirable to model actual forging practice. The specimen geometry utilized a 3:2 aspect ratio (height to diameter), but there is no standard. Some of the specimens had smooth ends while some had spiral grooves machined into the ends for possible better lubricant retention. Whether grooves were present or not did not seem to affect the recorded data. However, the presence of grooves was helpful in revealing how specimens deformed when the deformation was nonuniform (see Figs. 4 and 5).

Results

Figures 2 and 3 show microstructures resulting from 10 minute exposures of test material to 1800°F (982°C) and 1900°F (1038°C) respectively, followed by water quenching. Heating below the delta solvus, at 1800°F (982°C) does not result in grain growth. Delta precipitation at grain boundaries remains unchanged relative to unheated material (see Fig. 1), but there has been some additional delta precipitation and agglomeration within grains relative to billet material. Some grains appear to be free of delta phase which may be due to residual ingot segregation or to differences in etching as a result of grain orientation. Heating above the delta solvus at 1900°F (1038°C) results in grain growth as a result of solutioning of the delta phase. In the ten minute exposure, the grain size has coarsened to a uniform ASTM 5 from the billet ASTM 6.5 - 7.

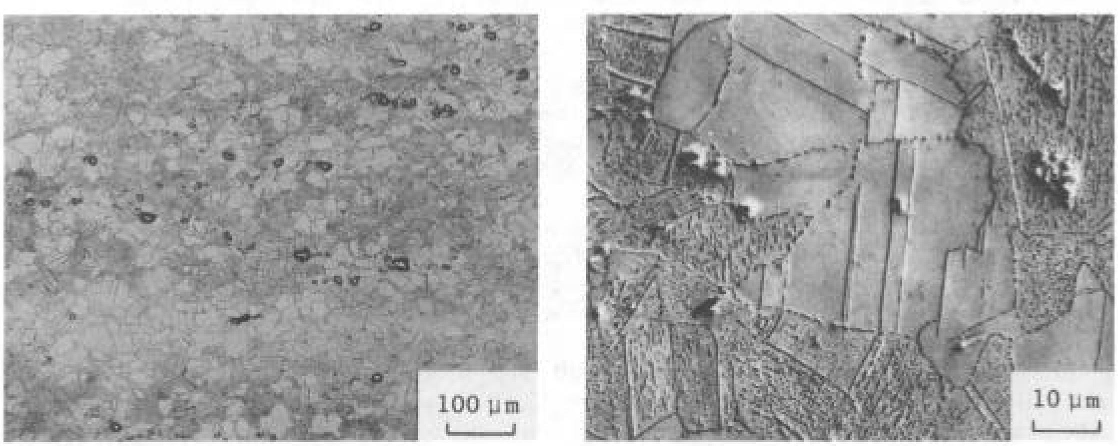


Figure 2 - Alloy 718 billet microstructure after 10 minutes at 1800°F (982°C), then water quench.

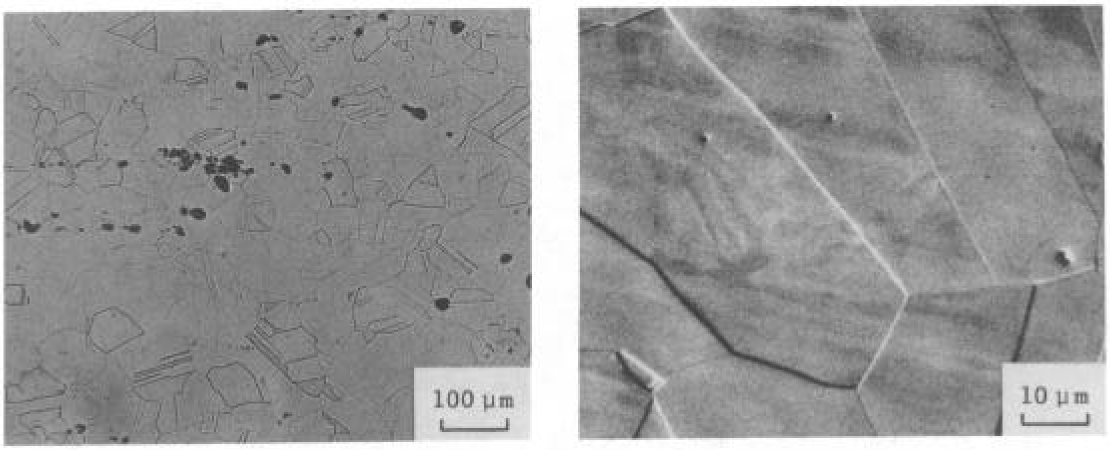


Figure 3 - Alloy 718 billet microstructure after 10 minutes at 1900°F (1038°C), then water quench.

Microstructures of deformed compression specimens were examined on a plane through the center of the specimen and perpendicular to the top and bottom surfaces of the specimen. If the specimen deformed uniformly, Fig. 4, any such plane was appropriate for microscopy. If the specimen did not upset uniformly, Fig. 5, then the microstructure was revealed by cutting along the major axes of the ellipse-shaped specimen. The nonuniform upsetting behavior was observed only at a strain rate of 10 sec^{-1} at 1800°F (982°C), while at 1600°F (871°C) it occurred at strain rates of 10^{-2} sec^{-1} to 10 sec^{-1}. Microstructures were mostly uniform within each specimen, except at the lowest test temperatures and highest strain rates where flow localization occurred. For example, the specimen shown in Fig. 5, tested at 1800°F (982°C) and 10 sec^{-1}, was found to have a uniform microstructure throughout (it is shown in Fig. 8), even though the specimen did not upset uniformly. In contrast, flow localization in a specimen tested at 1600°F (871°C) and 10 sec^{-1} is shown in Fig. 6.

Even in a single specimen that does not exhibit nonuniform deformation there are some small differences in grain size that result from the fact that the strains and strain rates throughout the compression specimen are not everywhere the same. For example, the grain size is slightly finer at the centers of the compression specimens than at the outer diameters. Also friction has an effect. Material at the top and bottom

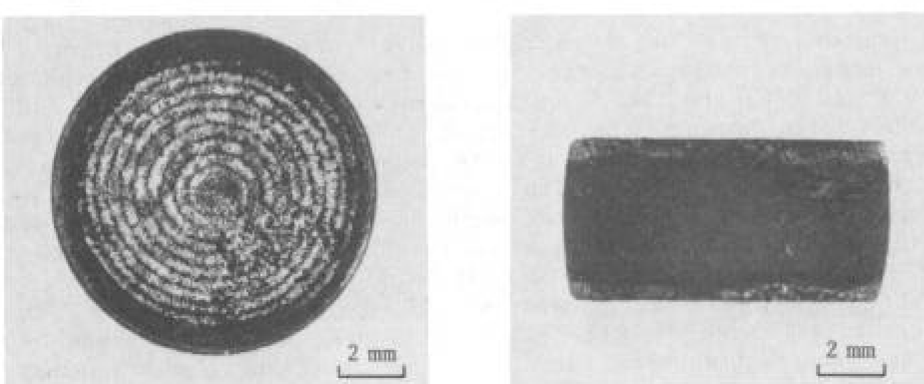
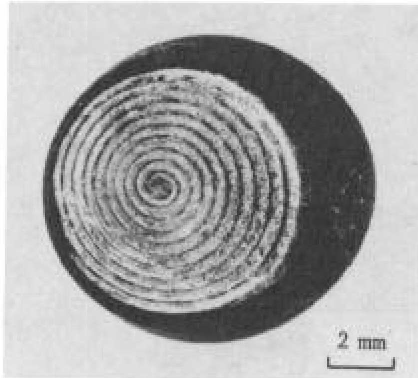


Figure 4 - Compression specimen deformed at 1900°F (1038°C) and 10 sec^{-1} to a true axial strain of 0.6.



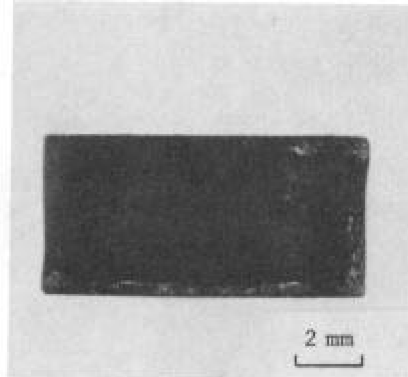


Figure 5 - Compression specimen deformed at 1800°F (982°C) and 10 sec^{-1} to a true axial strain of 0.6.

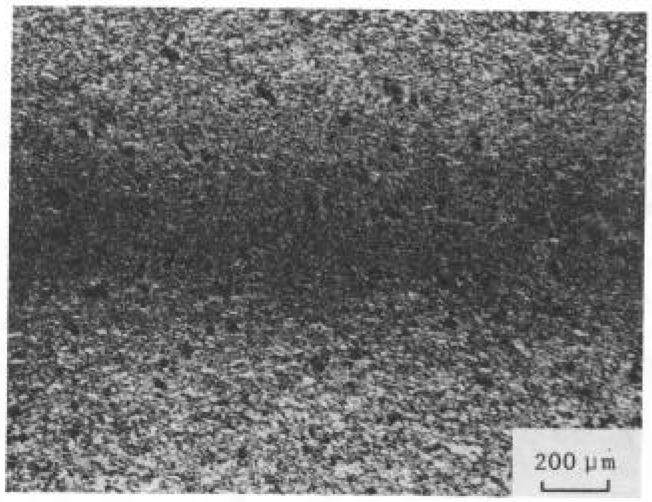
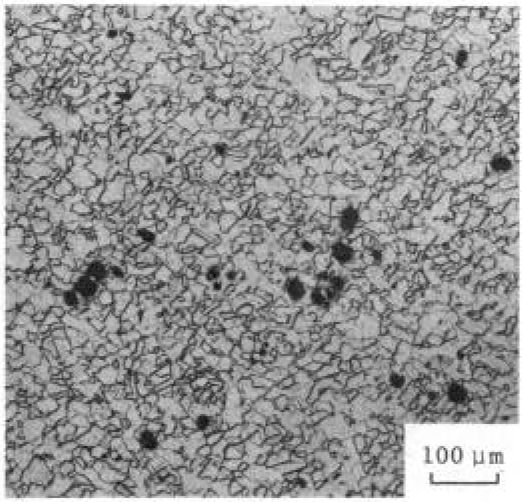


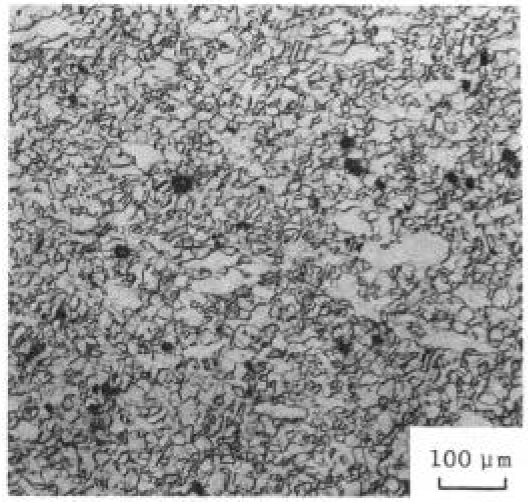
Figure 6 - Shear band in a specimen deformed at 1600°F (871°C) and 10 sec^{-1} to a true axial strain of 0.6.

surfaces of a specimen is deformed less than material in the center of a specimen. Carbide stringers that are revealed nicely in polished but unetched material show the areas affected by friction, called the friction cones. The friction cones in the specimens tested here were small.

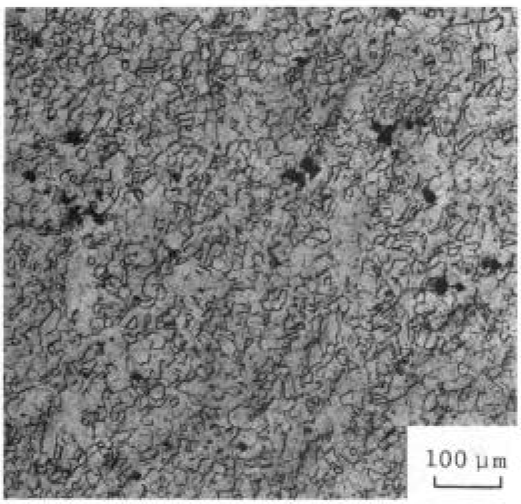
A number of as-forged microstructures are shown in Figs. 7 and 8. The microstructures in Fig. 7 are for deformation at a temperature of 1900°F (1038°C) and the five strain rates tested. At 1900°F (1038°C), above the delta solvus, the as-forged grain size is not very sensitive to strain rate over the range tested. At 10^{-3} sec^{-1}, the grain size is rated at average ASTM 9 with some grains as large as (ala) ASTM 7. At 10 sec^{-1}. the grain size is rated at ASTM 10 ala 9. These ratings take into account all the grains in the field of view. The grain size at the start of testing at 1900°F (1038°C) was ASTM 5 (Fig. 3), so the material has dynamically recrystallized during testing to the microstructures shown in Fig. 7. Furthermore, the flow curves indicate that the microstructures in Fig. 7 represent the steady-state microstructures. At the strains at which the compression testing was stopped (a minimum of 0.6), the flow stresses (and microstructures) are not changing with strain.



(a)



(b)



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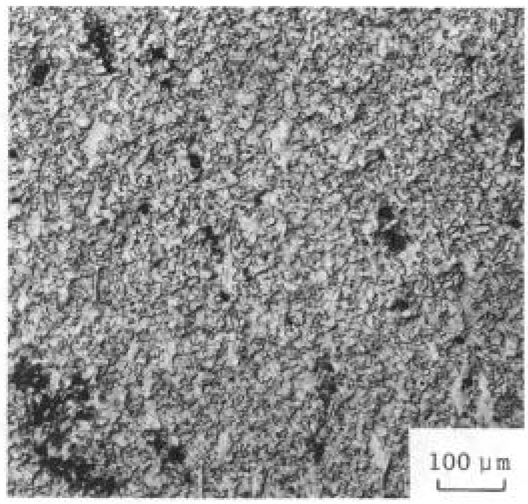

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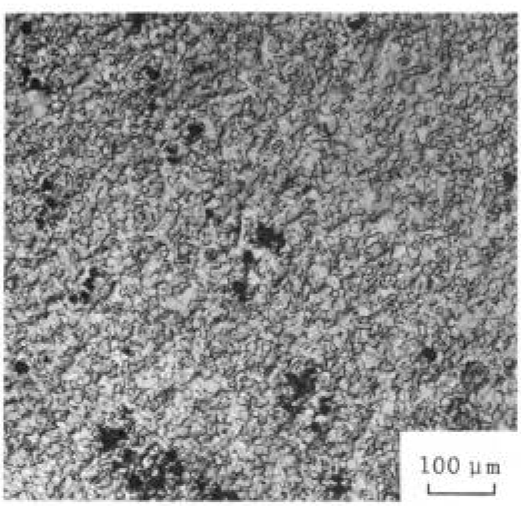
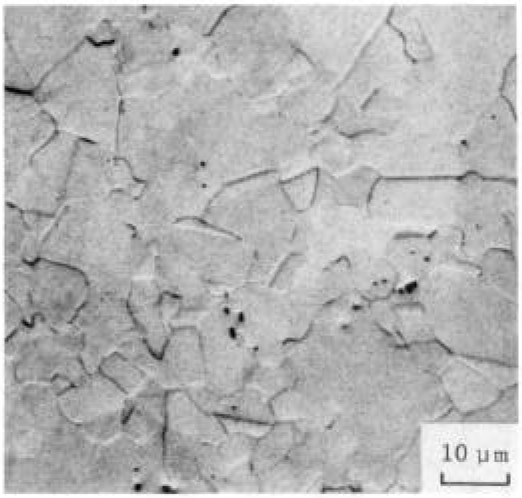
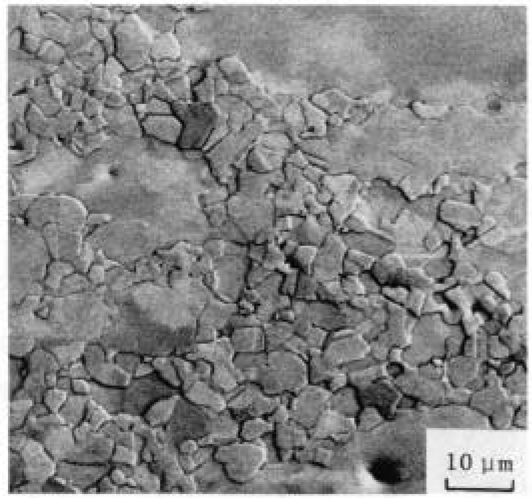


(e)

Figure 7 - As-forged microstructures for a test temperature of 1900°F (1038°C) and strain rates of: a) 10^{-3} sec^{-1}; b) 10^{-2} sec^{-1}; c) 10^{-1} sec^{-1}; d) 1 sec^{-1}; and e) 10 sec^{-1}.



(a)



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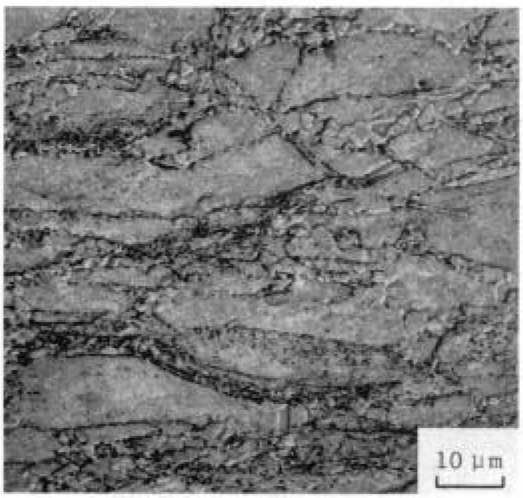

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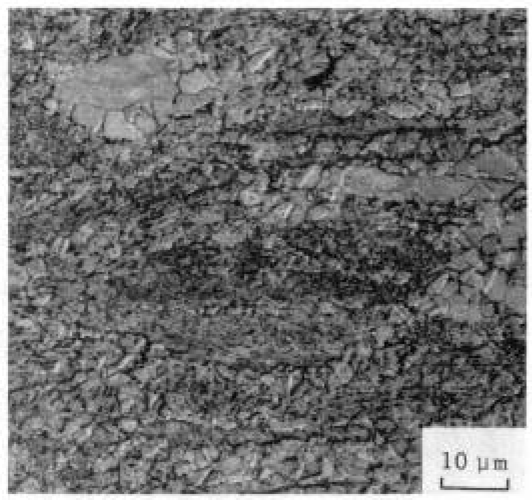

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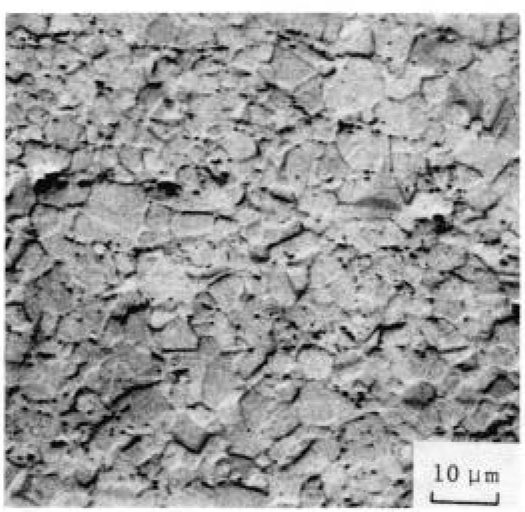

(e)

Figure 8 - As-forged microstructures for a test temperature of 1800°F (982°C) and strain rates of: a) 10^{-3} sec^{-1}; b) 10^{-2} sec^{-1}; c) 10^{-1} sec^{-1}; d) 1 sec^{-1}; and e) 10 sec^{-1}.

At 1800°F (982°C), below the delta solvus, two types of microstructure result from the testing - either a uniform dynamically recrystallized grain structure, or a necklace grain structure, Fig. 8. The necklace grain structure is a result of dynamic recrystallization that occurs preferentially at the grain boundaries that exist at the start of testing, resulting in a network of relatively fine grains surrounding larger, deformed, but unrecrystallized grains. At a strain rate of 10^{-3} sec^{-1}, the grain structure is a uniform ASTM 11 ala 9. At 10^{-2} sec^{-1} to 1 sec^{-1}, necklacing occurs. The necklace grain size ranges from ASTM 12 ala 11 at 10^{-2} sec^{-1}, to ASTM 14 ala 13 at 1 sec^{-1}. At 10 sec^{-1}, the grain structure is a uniform ASTM 13 ala 12. The flow curves again indicate that the microstructures in Fig. 8 are steady-state microstructures. At a strain of 0.6, the flow curve for the test at 1800°F (982°C) and the fastest strain rate, 10 sec^{-1}, is not changing with strain.

At test temperatures of 1700°F (927°C) and below, other microstructural results were obtained. As shown in Fig. 6, at the lowest test temperatures and fastest strain rates, shear bands formed. For some test conditions, no dynamic recrystallization occurred, including necklacing. The microstructure consisted of warm worked, distorted grains.

A way to present the microstructural data useful to the forge designer and the product metallurgist is to define, on axes of temperature and strain rate, important microstructural features such as grain size, whether necklacing occurs, and whether deformation is uniform or prone to shear band formation. Such a plot, prepared using microstructures obtained from many of the compression tests carried out, is drawn in Fig. 9. In Fig. 9, at each test condition examined, the average ASTM grain size is given, and the largest grain size observed is added in parentheses. Thus, ASTM 9 ala 7 is written 9(7). If necklacing occurred, the letter N is added next to the grain size rating. If necklacing occurred, the grain size rating is for the necklace grains, not for the distorted unrecrystallized grains. If no recrystallization occurred, this is indicated by UnRX. Finally, shear band formation is denoted by SB. If a grain size is reported for a specimen that exhibited such flow localization, the microstructure was examined in the shear band. Boundaries that delineate three different types of microstructural results are sketched on Fig. 9. The three different microstructures are shear bands, necklace structures, and dynamically recrystallized uniform grains. Specimens that exhibited warm working without dynamic recrystallization (UnRX) are included in the necklacing region. This is a map for billet material characterized by a uniform grain size of about ASTM 7 and a columbium content at the high end of the allowable range (5.44 weight % in this case).

Concluding Remarks

Compression testing yields a wealth of data that are put to use in different ways. Flow data are used by the forge process designer, and are essential for process modeling. The flow data are also used to derive different types of process maps. Analysis of the deformed specimens yields microstructural data and identifies tendencies for mechanical instability. All of this information is essential. This study has focused on one way to extract microstructural information from compression tests and organize it in a way that is useful to the forge process designer.

The Alloy 718 microstructural map sketched out in Fig. 9 is valid for a certain set of conditions. It is valid for billet material like that used in this study: billet with uniform grain size of about ASTM

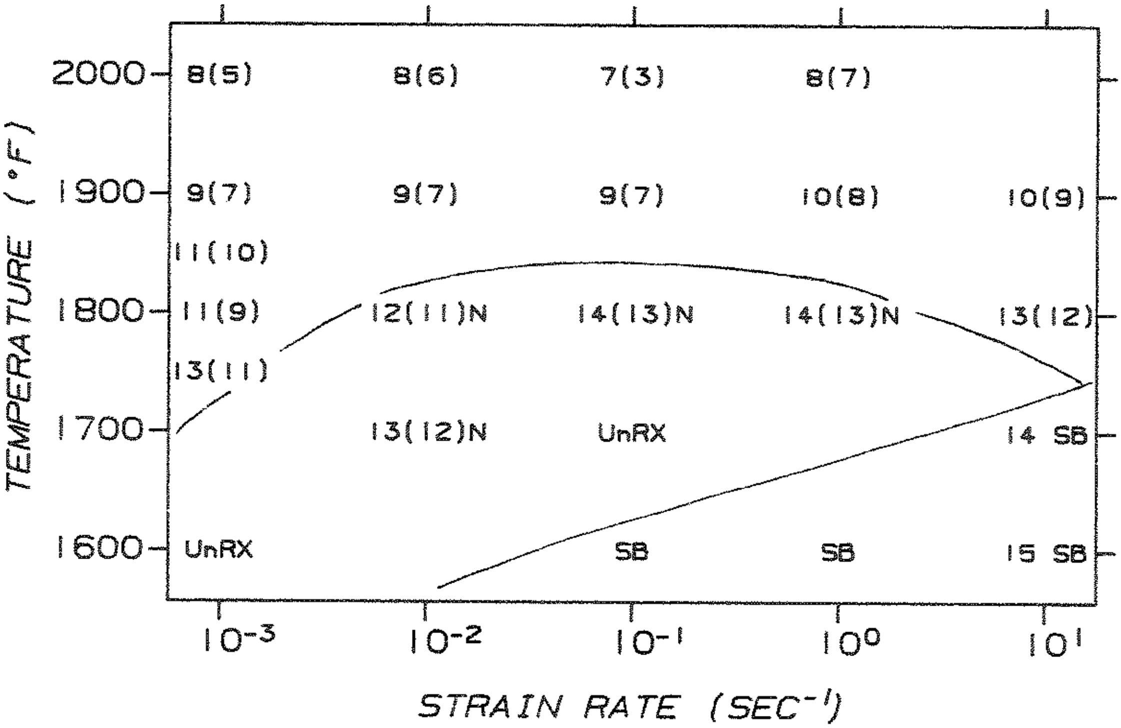

Figure 9 - A deformation map that highlights some as-forged microstructural features. Grain sizes are defined as follows: 9(7) means an average grain size of ASTM 9 with some grains as large as ASTM 7. N means that necklacing occurred. UnRx stands for unrecrystallized - no dynamic recrystallization took place. SB means that shear bands formed.

7 and with a chemistry, especially Cb content, like that given in Table I. The deformed microstructures, particularly at temperatures below the delta solvus, would be expected to be different for billet material that has a different starting microstructure. Some of the boundaries sketched on the map will be sensitive to the delta solvus; these will change with chemistry. The map is valid for compression testing procedures like those used here. Different parameters of time at temperature before testing, cooling rate after testing, or lubrication, would be expected to change the results.

The microstructural map can be used to guide design. It can also be used to help interpret forged microstructures which are determined not only by the forge temperature, strain rate, and strain, but also by billet chemistry, microstructure and homogeneity and by effects of friction, die lock, and die chill. Much Alloy 718 is forged near the delta solvus, both above it and below it, and the deformation behavior of Alloy 718 in this region is complex. This map and others for different types of starting billet, can help process design in this critical area.

References

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