THERMOMECHANICAL PROCESSING OF HAYNES ALLOY No. 188 SHEET TO IMPROVE CREEP STRENGTH

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An investigation was performed to seek improvements in the low strain (≤ 1%) creep strength of HAYNES alloy No. 188 thin gauge sheet, nominally .38mm (.015 in.) thick by means of thermomechanical processing. Results of the study indicate that significant improvements were achieved in sheet processed so as to obtain a high degree of preferred orientation after recrystallization.

INTRODUCTION

In the design of metallic heat shields for advanced re-entry and/or hypersonic vehicles, plastic deformation due to creep is considered to be a significant factor (1). Attention in design has been focused on low values of creep strain (≤ 1%) due to deflection limit criteria. Optimization of heat shields for maximum reuse with minimum weight further requires the use of thin gauge sheet materials. Thus, the successful candidate material must possess the required low strain creep strength in thin gauge form.

HAYNES alloy No. 188, a cobalt-base sheet alloy (Co-22Cr-22Ni-14W-1Mn-.35Si-.10C-.04La by w/o) developed by the Stellite Division of the Cabot Corporation, has shown promise for heat shield applications. Like most alloys, lower strengths than normal result when the material is produced in thin gauge form using standard commercial practices. The creep properties of HAYNES alloy No. 188 thin gauge sheet were not characterized in the initial development work (2). However, the reduced high temperature load-bearing capability of thin gauge sheet was indicated by the lower stress rupture properties obtained in sheet 0.25mm to 0.48mm (0.010-0.019 in.) thick. It was the

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objective of this program, therefore, to seek improvement of the low strain creep strength of thin gauge HAYNES alloy No. 188 sheet by modification of thermomechanical processing (TMP) procedures.

MATERIALS AND PROCEDURES

To provide a framework for comparison, baseline data were established for three production heats of HAYNES alloy No. 188 sheet nominally 0.38mm (0.015 in.) thick. These included low strain (≤ 1%) creep properties in the temperature range of 922K (1200°F) to 1255K (1800°F). In addition, the crystallographic textures and the microstructural characteristics of the baseline sheets were determined. Specific details of the methods and procedures used are given in (3).

Thermomechanical Processing Studies

The experimental program was performed on sheet produced in the laboratory from standard production, hot rolled plate feedstock nominally 4.56mm (0.180 in.) thick. All mechanical property testing was done by a single, inhouse testing group to eliminate lab-to-lab testing variations. Improvements in the low strain creep strength of HAYNES alloy No. 188 sheet nominally 0.38mm (0.015 in.) thick were sought using two different approaches. One approach examined thermomechanical processing designed to promote high degrees of preferred grain orientation in recrystallized thin gauge sheet. The other approach concentrated on thermomechanical processing to optimize grain size.

In the investigation of crystallographic texture on creep strength, an initial study was performed using strips measuring approximately 0.38mm x 28.57mm x 127cm (0.015 in. x 1.125 in. x 50 in.) which were produced from a single heat of material. The cold-rolling schedules were planned such that final cold reductions in thickness of 70%, 80% and 90% would be obtained. Three strips were processed to each level of final coldwork and then final annealed for 10 minutes at a temperature of 1394K (2050°F), 1450K (2150°F), or 1505K (2250°F)and rapid air cooled. The strips produced thus represented nine different final coldwork and annealing temperature combinations. The crystallographic textures of these sheets were first examined using incomplete pole figures which covered the central 55° of the stereographic projection (4). The initial experimental sheets were then screened to determine optimum creep strength using a standard quality control test condition of 1200K/41.4MPa (1700°F/6Ksi).

Following this initial study, an extensive low strain creep evaluation was performed on sheets measuring approximately 0.38mm x 12.7cm wide x 63.5cm long (0.015 in. x 5 in. x 25 in.) which were produced in accordance with the thermomechanical processing scheme judged to be optimum. The starting materials used to produce these sheets represented three different heats of HAYNES alloy No. 188 so that heat-to-heat variations would be taken into account.

In the investigation of grain size optimization, a laboratory processing study was first carried out to determine the thermomechanical processing required to produce sheets nominally 0.38mm (0.015 in.) thick having uniform grain sizes corresponding to ASTM 7-8, ASTM 5-6 and ASTM 2-4. The variables employed in this study were limited to amounts of coldwork, annealing temperature and time at temperature. Following the identification of the required processing schedules, strips measuring approximately 0.38mm x 28.6mm wide x 127cm long (0.015 in. x 1.125 in. x 50 in.) were produced to each grain size range from the same three heats of HAYNES alloy No. 188 starting material used in the investigation of crystallographic texture. These initial sheets were screened to determine the optimum grain size for low strain creep strength at a test condition of 1200K/41.4 MPa (1700°F/6Ksi).

RESULTS

Initial Thermomechanical Processing Studies

Investigation of Texture. Samples from the initial experimental strips were examined for crystallographic texture by preparing incomplete (111) pole figures. In all cases, the strips possessed the same well defined texture as that illustrated in Figure 1(a). Only the angular spreading of the high intensity areas was observed to vary with the different thermomechanical processing conditions. In order to obtain further definition of the texture type, the (220) and (200) pole figures were determined for the sample given 80% coldwork and final anneal at 1450K (2150°F), which was arbitrarily selected for this purpose. The resulting pole figures are shown in Figures 1(b) and 1(c). By comparing the three different pole figures generated to various standard projections of crystal orientations, it was found that a very satisfactory fit could be obtained by assuming the presence of two major textural components. These were (a) (110) parallel to the sheet plane with [$\bar{1}$10] parallel to the rolling direction, and (b) (112) parallel to the sheet plane with [$\bar{1}$10] parallel to the rolling direction. A composite standard projection showing these components is presented in Figure 1(d). By allowing for the occurrence of symmetry of poles across planes normal to the rolling and transverse directions, it can be seen that the composite projection accounts for the geometry of the high intensity regions observed in the experimentally determined pole figures. In comparison, the baseline sheets were not found to possess any strongly definable crystallographic texture.

A summary of the 1200K/41.4MPa (1700°F/6Ksi) 0.5% creep strain data obtained for the initial experimental strips is presented in Figure 2. The 1.0% creep data followed the same pattern. At each level of final coldwork, the creep strength was found to increase with increasing annealing temperature. This behavior was correlated to a major extent to the final grain sizes obtained. Specifically, for final annealing temperatures of 1394K (2050°F) 1450K (2150°F) and 1505K (2250°F), the resulting grain sizes were found to be in the ranges of ASTM 8-10 or finer, ASTM 6-7 1/2, and ASTM 3-1/2 - 5 1/2, respectively. Only the experimental sheets annealed at the highest temperature were found to possess creep strengths higher than the baseline production sheets, which had grain sizes in the range of ASTM 6-6 1/2. However, as it will be shown later, the creep strengths of the textured sheets could not be accounted for on the basis of grain size alone.

The original duplicate test, creep data were not sufficient to determine statistically significant differences among the experimental sheets annealed at the highest temperature. Therefore, the test plan for these sheets was expanded to five replicate tests. Statistical comparisons were then made using the t-test with the data transformed into log units. This analysis included the data sets for the times to 0.5% and 1.0% creep strain. The results of the statistical tests indicated that all of the sheets annealed at the highest temperature were significantly superior to the baseline sheets at confidence levels greater than 95%. Among the experimental sheets, tests between the 70% and 80% coldwork levels indicated that significantly higher creep strengths were obtained with 80% coldwork ($\geq$ 99% confidence level). Tests between the 70% and 90% final coldwork levels indicated a superiority of 90% coldwork for 0.5% creep strain. Due to differences in data scatter, however, the superiority of 90% coldwork could not be firmly established for the analysis of 1.0% creep strain data ($\sim$ 89.4% confidence

(a) (b)

(c) (d)

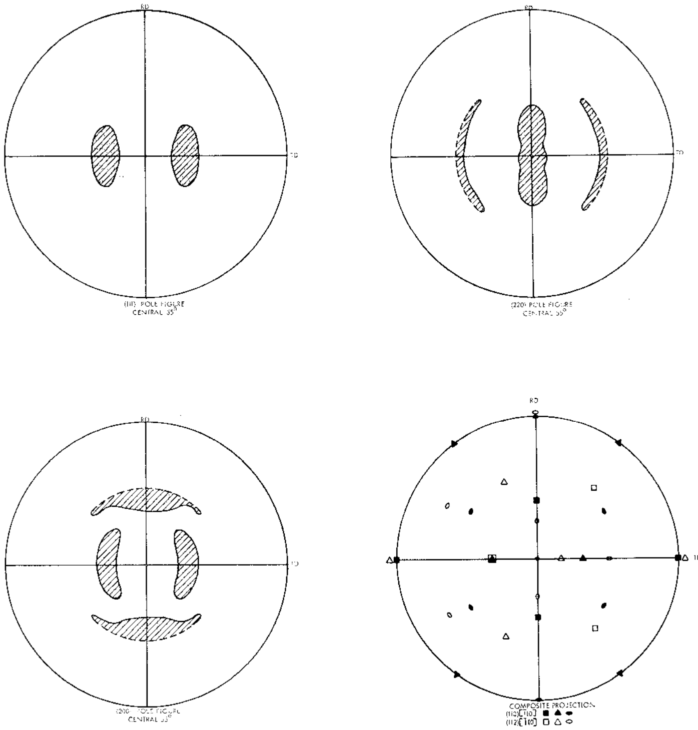

Fig. 1. Analysis of Pole Figures for 80% Final Coldwork: (a) (111) (b) (220) (c) (200) (d) (110) [$\bar{1}$10]and (112) [$\bar{1}$10] Composite Projection.

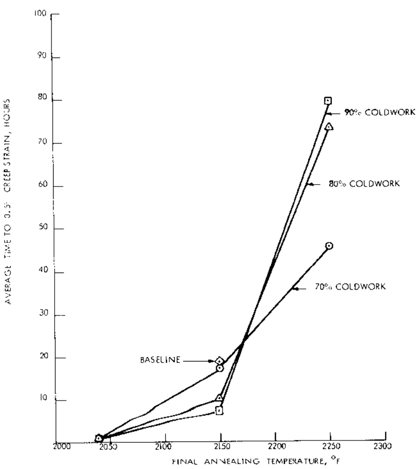

Fig. 2. The Effect of Texture TMP on 0.5% Creep Life at 1200K/41.4 MPa (1700°F/6Ksi)

level based on 2-tailed probabilities). Tests between the 80% and 90% final coldwork samples revealed no significant differences in either the 0.5% of 1.0% creep strain data. Based on these results, the combination of 80% final coldwork followed by an anneal at 1505K (2250°F) was judged to represent the optimum thermomechanical processing conditions for producing a textured HAYNES alloy No. 188 thin gauge sheet.

Investigation of Grain Size

Samples from the experimental grain size study strips were first examined for crystallographic texture by preparing (111) incomplete pole figures. The sheets produced to a grain size range of ASTM 2-4 were found not to possess a discernible texture. These sheets had been prepared by imposing a critical strain (3% elongation) prior to a final anneal at 1463K (2175°F). Definite texturing was found in the ASTM 5-6 and ASTM 7-8 sheet lots. The forms of the pole figures obtained were the same as those observed in the texture study sheets. The degree of texturing, based on the angular spreading of the regions of high intensity, could be correlated to the amount of final coldwork. That is, the high intensity areas were more diffuse for the ASTM 5-6 sheets (57% final coldwork) than for the ASTM 7-8 sheets (75% final coldwork).

The creep strength evaluation of the experimental grain size study sheets was conducted using a test condition of 1200K/41.4MPa (1700°F/6Ksi). A summary of the data obtained is given in Table 1. The data indicated that none of the experimental sheet lots had creep strength superior to the baseline sheets. Statistical comparisons of the data sets revealed no significant differences between the sheet lots with grain sizes of ASTM 2-4 and ASTM 5-6, but both were found to be significantly superior to the sheet lot with a grain size of ASTM 7-8. The ASTM 7-8 grain size sheet lot was also significantly inferior to the baseline production sheets.

Table 1. Average 1200K/41.4MPa (1700°F/6Ksi) Creep Test Data for Baseline and Grain Size Study Sheets

Sheet Lot	Average Time to Indicated Creep Strain, Hrs.*	
	0.5%	1.0%
Baseline	19.1	42.8
ASTM 2-4	22.8	62.2
ASTM 5-6	19.0	44.3
ASTM 7-8	8.1	16.0

* 6 tests/sheet lot

EVALUATION OF OPTIMUM TEXTURE SHEETS

Creep Life Evaluation

In order to obtain a more detailed characterization of the creep strengths of the sheets given optimum texture thermo-mechanical processing, additional creep testing was conducted on larger sized sheets at temperatures of 922K (1200°F), 1144K (1600°F) and 1255K (1800°F). All tests were performed using longitudinally oriented samples. Characterization of the creep data was accomplished by subjecting the 0.5% and 1.0% creep strain data to a least squares optimization of the Larson-Miller parameter equation with the regression equation in the following form (5):

$$P = T\,(\log t + 17) = C_2 + C_3 \log S + C_4\,(\log S)^2$$

where T = absolute temperature (K or °R)
t = time to given creep strain, hrs.
s = stress (MPa or Ksi)
C_2, C_3, C_4 = optimized constants

Comparison plots of the results obtained for the baseline and optimum texture sheets are presented in Figures 3 and 4. The minus 2-sigma and minus 3-sigma limits shown in the figures allow significant differences in the creep properties to be appreciated. That is, only 2.27% of the test results at a given creep test condition are expected to be less than the value indicated by the minus 2-sigma limit, and only 0.13% are expected to be less than the value indicated by the minus 3-sigma limit.

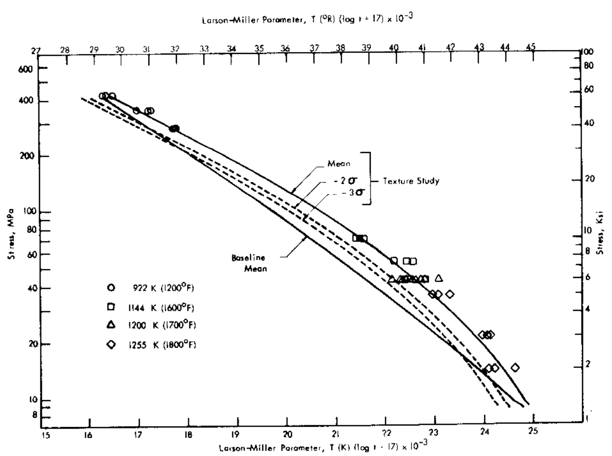

Fig. 3

Comparison of 0.5% creep strengths of baseline and texture study sheets

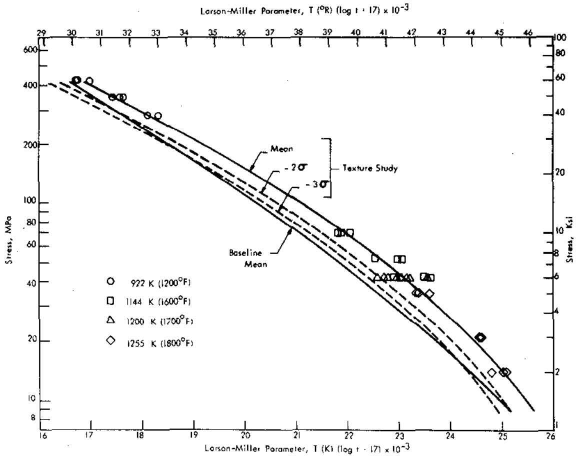

Fig. 4

Comparison of 1.0% creep strengths of baseline and texture study sheets.

From the figures, it can be seen that the minus 3-sigma limits of the optimum texture sheets lie above the baseline average values over a range of test conditions corresponding to approximately 206.8MPa/18 x 10^3 LMP-K (30Ksi/32.5 LMP - °R) to 17.2 MPa/23.5 LMP-K (2.5Ksi/42.3 LMP - °R). Thus, the textured sheets demonstrated a very significant improvement in low strain creep strength over the baseline sheets.

Examination of Microstructures After Creep Testing

The differences noted between the textured and the baseline sheets strongly suggested the possibility of microstructural differences. To test this hypothesis, a brief investigation was conducted on samples which had been creep tested at 1200K/41.4MPa (1700°F/6Ksi). Representative transmission electron micrographs of structures observed in the baseline and textured sheets are illustrated in Figures 5 and 6. Typical dislocation structures in the baseline sheets consisting of tangles produced by the intersection and reaction of glide dislocations, and pile-ups at relatively large carbide particles and grain boundaries. In contrast, in the textured sheets there was a marked tendency toward the formation of dislocation sub-boundaries. These occurred in the form of loosely constructed subgrain walls or as well defined planar networks. Fine carbide precipitates were also evident within the dislocation boundaries and on tangled dislocations.

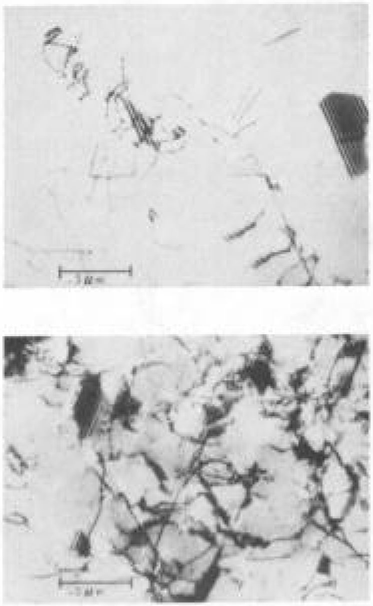

Fig. 5. Substructures Observed in Baseline Sheets

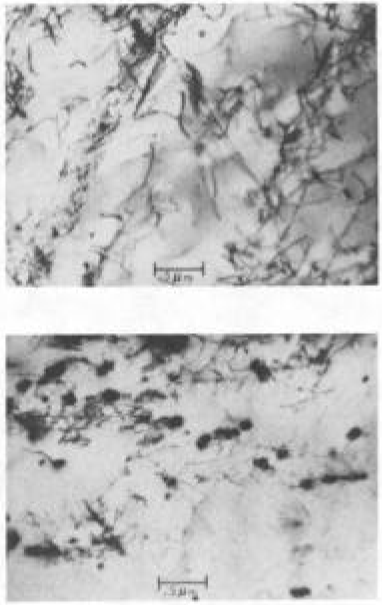

Fig. 6. Substructures Observed in Textured Sheets

SUMMARY AND CONCLUSIONS

The primary objective of the program was to obtain improvements in the low strain ($\leq$ 1%) creep strength of HAYNES alloy No. 188 thin gauge sheet by means of TMP. To achieve this goal, two major approaches were taken. One focused attention on TMP designed to promote a preferred crystallographic texture after recrystallization. The other concentrated on grain size control. Results of the investigation indicated that significant improvements in low strain creep strength were obtained in sheets with a strong recrystallized texture. The TMP considered to given optimum results consisted of 80% final coldwork followed by an anneal at 1505K (2250°F) for 10 minutes. The major components of the texture resulting from this TMP schedule, with respect to the plane of the sheet and the rolling direction, were identified as (110) [$\bar{1}$10] and (112) [$\bar{1}$10].

Based on stress versus Larson-Miller parameter, correlations obtained for 0.5% and 1.0% creep life data, the minus

3-sigma creep life minimums of the textured sheets were found to lie above the baseline average values over a range of test conditions corresponding to approximately 206.8MPa/18 x 10^3 LMP-K (30Ksi/32.5 x 10^3 LMP-°F to 17.2MPa/23.5 x 10^3 LMP-K (2.5 Ksi/42.3 x 10^3 LMP-°R.

The improved low strain creep strength of the textured sheets can be attributed to the combination of enhanced sub-boundary formation and the precipitation of carbides on the dislocation structures formed during creep.

ACKNOWLEDGEMENT

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