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Stress relaxation of nickel-based superalloy helical springs at high temperatures

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ABSTRACT

The creep resistance of materials in spring applications is generally acknowledged to be well below that observed in other applications. Helical springs formed from three candidate nickel-based superalloys, Nimonic 90, René 41 and Haynes 282, have been tested under compression in order to gain some insight into this phenomenon. Stress relaxation tests conducted at 600–700 °C found that, under constant displacement, the degradation of the spring force is one to three orders of magnitude faster than would be predicted from creep data from extruded samples under equivalent tensile loading. An analytical model for torsional creep in helical springs is derived from a modified version of the Dyson creep model. The effects of various microstructural features on the deformation rate are considered. Effects such as the coarsening of the precipitate-strengthening gamma-prime phase, tertiary creep due to dislocation multiplication, damage evolution and hardening due to transfer of the stress to the particles from the matrix are concluded to make negligible contributions. It is predicted that the poor performance of the springs is due to the very high population of geometrically necessary dislocations that result from the bending and twisting of the wire into a helical coil. It is expected that these dislocations are resistant to conventional heat treatments, resulting in a persistent residual stress field and a large number of dislocations to facilitate the creep process. In some cases, the stress relaxation is found to be so fast that the precipitate hardening of the alloy is too slow to prevent significant initial degradation of the spring.

1. Introduction

Metallic wire, helical coil compression springs continue to be of considerable practical interest in many high temperature plant applications, but to date have failed to live up to expectations based upon axial creep properties [6]. Springs of this type are used extensively in power plant surface clearance control systems. The inspiration to delve further into the issues of springs for high temperature service arises from a potential requirement for spring materials to match the needs of ever increasing power plant temperatures. This will enable increased operating temperatures and reduced CO_2 emissions per megawatt.

A mechanical modelling approach has been adopted to highlight those materials and engineering characteristics that would best lead to a wire wound helical coil compression spring that will operate at higher temperatures more in keeping with the known high temperature properties of the parent material. The modelling approach has been matched with practical investigation of coil springs in three common usage nickel-based superalloys well known for their high temperature creep strength Nimonic 90, René 41 and Haynes 282. The materials selected are available as fine wire products and all exhibit good fabricability in coil forming.

Nimonic 90 was developed as an age-hardenable creep resistant alloy for temperatures up to about 920 °C. It has good ductility and is typically used in turbine blades, ring sections, hot working tools, forgings and high temperature springs [15]. René 41 was designed to be used in high stress applications within the 650–980 °C temperature range. René-41 is difficult to fabricate due to its higher gamma-prime fraction and it also work hardens rapidly, requiring frequent annealing stages. As a material with good resistance to oxidation and corrosion, it is often used in applications such as after-burner components, turbine casings and fasteners [17]; however, it is known to suffer from strain age cracking. Haynes 282 is a more recent alloy developed as a successor to Waspaloy and René-41. It combines good thermal stability, weldability, and fabricability not found in many commercial alloys, and has excellent creep strength equal to that of René-41, in the temperature range of 649–927 °C. Slow gamma-prime precipitation kinetics result in excellent ductility in the as-annealed state. It is often used in components in critical areas of

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gas turbines, combustors, compressors and exhaust/nozzle applications [17].

The experimental procedure for measuring the stress relaxation in the springs is outlined in Section 2. A simple, analytical model for this stress relaxation is developed in Section3. Section 4 compares the predictions of the model with the experimental results and proposes explanations for the lower than expected performance of nickel-based superalloy springs and how it can be improved.

2. Materials and experimental procedure

The primary objective of the study was to determine the compressive stress relaxation behaviour of closely wound helical springs suitable for operation at temperatures in the range of 600–750 °C. Accordingly, three creep resistant nickel-based alloys, Nimonic 90, Rene 41 and Haynes Alloy 282, were selected as potential candidates for applications within this temperature range. In each case the alloys were supplied to spring manufacturers as solution treated 30% cold drawn to 2.5 mm diameter wire, i.e., in the 'spring tempered condition,' as is normal for wire coil spring manufacture. The springs were then cold wound to the required dimension on a mandrel and subsequently given a precipitation hardening treatment appropriate to each alloy. The Nimonic 90 springs were manufactured by Alstom Power and the René 41 and Haynes 282 springs were manufactured by European Springs and Pressings Ltd. Details of the nominal compositions of the alloys are shown in Table 1.

The solution treatment and post spring winding heat treatments for the three alloys are given in Table 2. Note that Haynes 282 is the only alloy that undergoes a two-stage precipitation hardening heat treatment. The René 41 requires the highest precipitation hardening conditions to achieve the optimum precipitate distribution for high temperature strength and ductility, as it has the highest concentration of gamma-prime forming elements.

In the present studies the helical springs wound from 2.5 mm diameter wire were 29 mm in height with outside and inside diameters of 19 mm and 14 mm, respectively, as shown in Fig. 1. Each spring consisted of five free coils and two end coils which were tapered and flattened. Following measurement of the overall free length of each of the springs, they were fully compression tested in an Instron Tensometer to determine their load/displacement characteristics, as shown in Fig. 2. This enabled the spring constant for each candidate material to be determined as well as the load required for any predetermined compression of each spring. No significant difference between the spring constants for the three alloys was observed.

The compressive stress relaxation tests were conducted on helical springs using the procedure described by Betteridge [22]. In order to determine the effects of long-term thermal exposure on the compressive stress relaxation of the springs, samples of each alloy were placed on a 12 mm diameter stainless steel bolt with washers at each end and pre-compressed to lengths of 19 mm, 21 mm and 23 mm, as shown in Fig. 1. Nuts were screwed down to lock the displacements and the loads corresponding to each displacement condition recorded. The bolted assemblies for each of the three alloys and three compressive displacements were then placed in furnaces set at 600 °C, 650 °C and 700 °C for exposure durations of 1, 3, 10, 30, 100, 300 and 1000 h. Three springs were used for every test and the remnant force reported for each test is the average over the three results. In every case the standard

Table 1
Nominal compositions in wt% of the three nickel-based superalloys in the experimental trial: Nimonic 90 (N90), René 41 (R41) and Haynes 282 (H282).

wt%	Ni	Cr	Co	Mo	Ti	Al	Fe	Mn	Si	C	B
H282	57.7	19.57	10.23	8.5	2.1	1.43	0.37	0.02	0.05	0.061	0.006
N90	53	19.5	18	N/A	2.4	1.4	3	1	1.5	0.13	N/A
R41	52.5	19	11.06	9.67	3.11	1.56	2.93	0.07	0.05	0.08	0.006

Table 2
Solution and final precipitation heat treatments for the superalloy wire and helical springs (AC=air cooled).

Alloy	Wire solution treatment temperatures (°C)	Spring precipitation treatment temperatures (°C)
Haynes 282	1150 °C rapid cool	2 h 1010 °C AC+8 h 788 °C AC
Nimonic 90	1150 °C rapid cool	4 h 750 °C AC
René 41	1080 °C rapid cool	16 h 760 °C AC

Fig. 1. The spring in the bolt assembly. The ends of the springs are flattened and tapered. The spring is subjected to a fixed compressive displacement δ using a tightened nut and bolt.

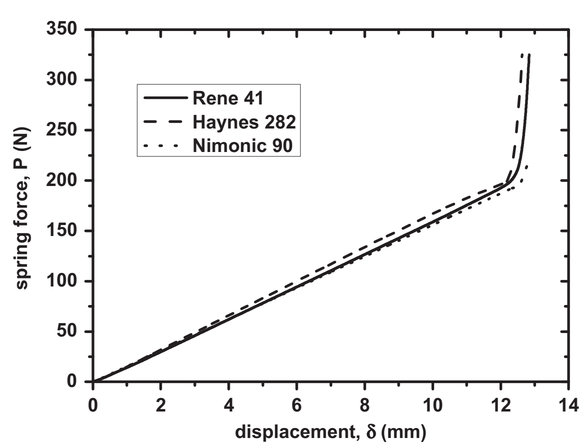

Fig. 2. Compressive load–displacement plots for the springs in the as-supplied condition.