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EFFECT OF PREDEFORMATION ON FATIGUE LIFE – EXPERIMENTAL CHARACTERIZATION AND DESCRIPTION BY MEANS OF A NEW PARAMETER

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ABSTRACT

Isothermal cyclic deformation tests were carried out on two nickel-base alloys (Nimonic 105 and Nimonic 75) after monotonic predeformation to various strains. The test temperatures ranged from room temperature up to 800°C, and plastic strain amplitudes between 0.025% and 0.25% were applied. The effect of predeformation was found to lose importance with increasing temperature, increasing plastic strain amplitude, decreasing prestrain and decreasing influence of particle strengthening. Appreciable changes in the crack initiation process and the dislocation arrangement resulted from predeformation. However, the change in the cyclic stress-strain response was identified to be the main reason for the effect of predeformation on fatigue life. Consequently, a new parameter S_{P_SWT} was derived which is based on the values of the Smith-Watson-Topper damage parameter obtained in fatigue tests on predeformed and not predeformed samples, respectively. It was shown that S_{P_SWT} is suitable to quantitatively describe the effect of loading conditions on the prehistory dependence and can successfully be applied for a simple and temperature-independent prediction of the influence of a predeformation on fatigue lifetime.

KEYWORDS

Predeformation, prehistory dependence, nickel-base alloys, cyclic stress-strain behaviour, microstructure, fatigue lifetime, damage parameter, high temperature

INTRODUCTION

Microstructure-related and mechanism-oriented studies on the cyclic deformation behaviour of metals and alloys mostly deal with materials in well-defined annealed starting conditions, in order to obtain results that are both definite and reproducible. Consequently, from all the parameters which are known to strongly influence cyclic stress-strain response and fatigue lifetime, such as loading amplitude, temperature and testing mode, least is know about the parameter mechanical prehistory. However, almost all engineering materials used in structural applications undergo a (thermo-)mechanical pre-treatment, either during the fabrication process or as a means to optimise the mechanical properties. Hence, the prehistory dependence of the cyclic deformation behaviour is on the one hand of high technical significance and on the other hand a complex scientific challenge.

Earlier studies which were focussing on single-phase fcc metals and alloys indicated the important role of the dislocation slip character [1-3]. In the case of planar slip, even a small monotonic prestrain gives rise to an increase of the stress amplitude during strain-controlled cyclic loading. Since this stress increase retains until failure, the cyclic stress-strain curve (css curve) is shifted upwards by predeformation (prehistory dependent behaviour). As opposed to planar-slip materials, simple and general statements are not possible for materials showing wavy dislocation glide. The behaviour is determined not only by the extent of predeformation, rather the amplitude of the subsequent cyclic loading plays also a significant role. Tendentiously the dependence on a mechanical prehistory ceases at a small predeformation in combination with high plastic strain amplitude. It should be noted in this context that the term prehistory dependence relates only to the mechanical behaviour. As shown in [4], very similar stress-strain responses may result from different types of dislocation arrangements formed during cycling without and after predeformation, respectively.

The results presented are part of a comprehensive study aimed at a detailed understanding of the influence of a monotonic room-temperature predeformation on the high-temperature fatigue behaviour of nickel-base alloys [5]. The emphasis in this paper is put upon cyclic lifetime effects. A simple parameter is introduced which allows to quantify the degree of the influence of relevant loading parameters on both the cyclic stress-strain response and fatigue life and therefore applies to a prediction of predeformation-induced changes in the number of cycles to failure N_f. Microstructural aspects are only dealt with as far as they help to define the applicability range of this predeformation parameter. More details on the microstructural and mechanistic aspects are given in [6].

EXPERIMENTAL DETAILS

The materials studied were two polycrystalline nickel-base alloys, Nimonic 75 and Nimonic 105, which were tested in three different precipitation conditions. Nimonic 75 is a precipitate-free nickel-base superalloy and was used to represent the behaviour of the matrix of Nimonic 105 (precipitate-free condition). In order to improve the comparability to this particle-strengthened material, the mean grain size of Nimonic 75 was adapted to the one of Nimonic 105 by means of an annealing treatment that led to a mean grain size of 60µm. Nimonic 105 was used in two different heat-treated conditions. After a solution annealing with subsequent water quench, an ageing at 850°C for 16 hours was applied to establish the peak-aged condition that corresponds to the hardness maximum at RT. The over-aged condition resulted from an annealing at 1000°C for 500 hours. The peak-aged condition is characterised by spherical γ' precipitates of a mean particle diameter of 73 nm at a volume fraction of 43%. The over-ageing treatment led to a γ' volume fraction of 38%. In this condition, the γ' precipitates were present in three superimposed size distributions with mean sizes of 32nm, 138nm and 665nm. As a consequence of the existence of small precipitates in the over-aged condition, the cyclic deformation behaviour of both conditions was found to be very similar and will therefore be reported jointly.

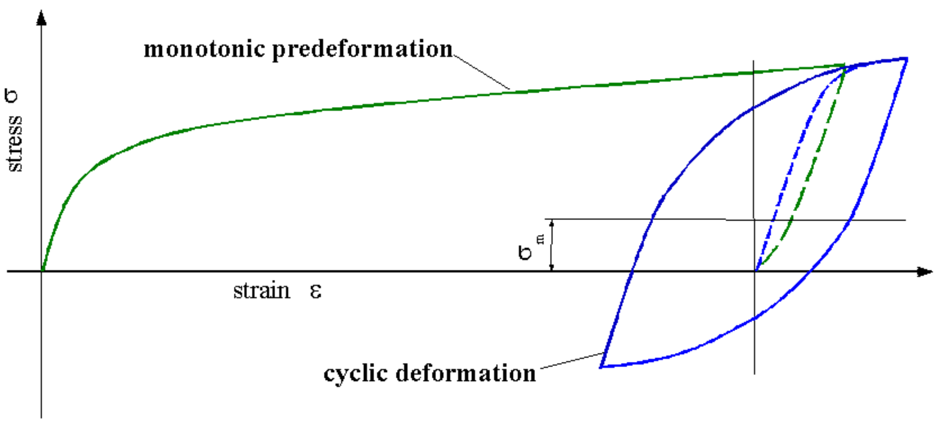

Figure 1: Effect of tensile predeformation on position of hysteresis loop

Specimens with a cylindrical gauge length of 6mm in diameter were tested in an electrohydraulic servocontrolled test system equipped with high frequency heating. The fatigue tests were performed at room temperature (RT), 400°C, 600°C and 800°C. True plastic strain control in combination with a triangular command signal was applied in all fatigue tests in such a way that the plastic strain rate was held constant at a absolute value of $5 \cdot 10^{-4}\ s^{-1}$. Plastic strain amplitudes $\Delta\varepsilon_{pl}/2$ ranging from 0.025% to 0.25% were used and were kept constant throughout the test (irrespective of a continuous change in Young´s modulus E) by means of a superimposed control of the plastic strain value at zero stress.

Predeformation was mainly carried out as monotonic tensile deformation up to certain levels of total strain ranging from 0% to 8% in steps of 2%. The basic effect of predeformation on the position of the hysteresis loop is illustrated in Figure 1. After tensile loading and unloading to zero stress the subsequent cyclic deformation leads to an asymmetric stress-strain hysteresis loop, since the deformation resistance is larger in tension as compared to compression. Hence, a positive mean stress σ_m results.

RESULTS AND DISCUSSION

The dislocation slip character in the matrix of Nimonic 105 and in the precipitate-free Nimonic 75 is planar, as expected for the Ni-Cr system [7]. Hence, dislocation glide during cyclic loading of Nimonic 75 is mainly restricted to single active slip planes. The main effects of prestraining seem to be a reduction of slip plane spacing and an increase of dislocation density within these planes [8]. The cyclic deformation behaviour of Nimonic 105 is governed by a strong dislocation/precipitate interaction. At low and moderate temperatures, cutting of γ' particles by dislocation pairs prevails, while at high temperatures Orowan bypassing takes place and no slip bands are appreciable. Figure 2 illustrates the effect of predeformation on the dislocation arrangement of Nimonic 105 at 800°C. Since prestraining was carried out at room temperature, slip planes are introduced which seem to remain active during high-temperature cyclic deformation (Fig. 2b) in addition to the individually gliding dislocations and Orowan loops which are typical of this temperature range (Fig. 2a).

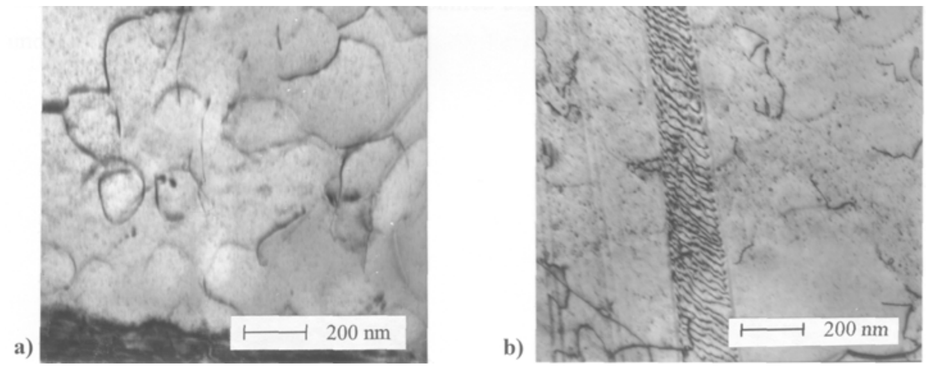

Figure 2: Dislocation arrangement in Nimonic 105 (over-aged) formed at 800°C and $\Delta\varepsilon_{pl}/2$=0.025% without predeformation (a) and after a tensile prestrain of 2% (b)

An example for the change of the location of crack initiation is given in Figure 3. In general, it was found that without predeformation crack initiation at low temperature takes place transgranularly at slip bands in the surface, whereas at high temperatures cracks form in the bulk of the material in the form of wedge cracks at grain boundary triple points and cavities. Predeformation gives rise to surface steps and therefore favours crack nucleation at the surface (Fig. 3b).

As will be shown later by the successful application of the Smith-Watson-Topper damage parameter, these changes in dislocation arrangement and crack initiation site due to prestraining do not seem to strongly and directly affect cyclic life. Rather, the influence of predeformation on the cyclic stress-strain response, which however is at least an indirect consequence of the modified microstructure, appears to be mainly responsible for the life time alteration. As already pointed out by means of Figure 1, the type of predeformation used in this study leads not only to a change in the stress amplitude during subsequent plastic strain controlled cycling, but also gives rise to a positive mean stress, if prestraining is carried out in tension, and vice versa. The schematic respresentation given in Figure 4 documents that at a constant temperature and constant plastic strain amplitude both stress amplitude and mean

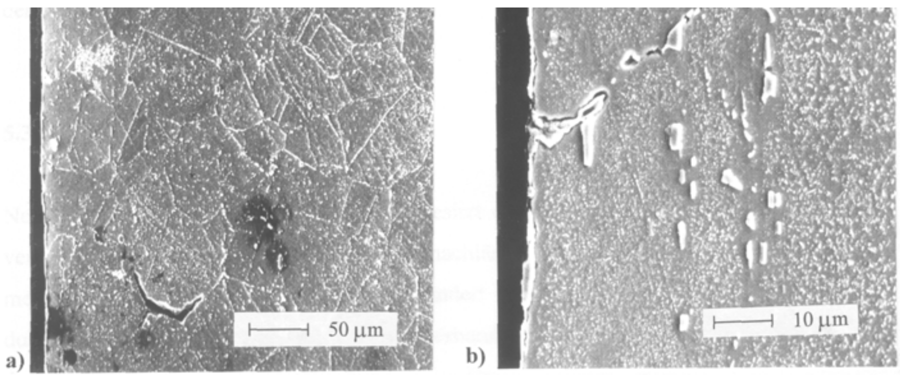

Figure 3: Cross sections showing fatigue crack initiation sites in Nimonic 75 (800°C and $\Delta\varepsilon_{pl}/2$=0.025%) without predeformation (a) and after a tensile prestrain of 8% (b)

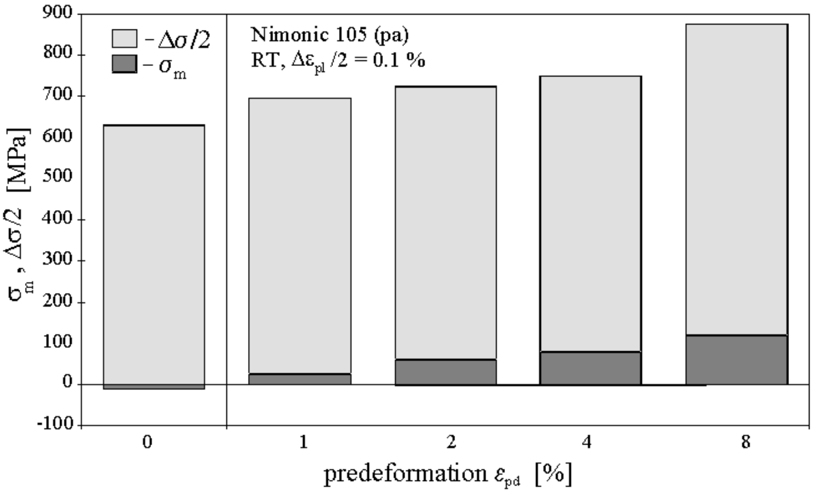

Figure 4: Effect of tensile prestrain on stress amplitude and mean stress at half fatigue life of Nimonic 105 (peak-aged) at $\Delta\varepsilon_{pl}/2$=0.1% and room temperature

stress usually increase with increasing degree of predeformation. However, it is important to mention that under certain conditions a decrease of Δσ/2 resulted from the mechanical prehistory.

A systematic evaluation of all the tests carried out showed the expected general trends that the extent of change in the stress-strain response (the history dependence) decreases with increasing temperature of subsequent cyclic loading, and with increasing plastic strain amplitude. Conversely the history dependence increases with increasing degree of predeformation (Fig. 4) and enhanced significance of particle strengthening.

The Smith-Watson-Topper parameter P_{SWT} [9] was appied to the cyclic stress-strain data at half life, since this damage parameter takes the predeformation-induced mean stress in a very simple and direct way into account.

$$P_{SWT} = \sqrt{\left(\frac{\Delta\sigma}{2} + \sigma_m\right)\frac{\Delta\varepsilon}{2}E} \tag{1}$$

P_{SWT} has shown in many earlier studies to be of similar capability of predicting cyclic life as those damage parameters which contain an adjustable variable [10]. A representation of P_{SWT} versus the experimentally observed number of cycles to failure is depicted in Figure 5 for all tests performed at room temperature. Irrespective of the extent of predeformation applied, rather narrow bands describe the correlation of P_{SWT} and cyclic life for each material. For each temperature a representation similar to Fig. 5 resulted. However, the shape and position of the respective P_{SWT} *vs.* N_f curves was found to depend on temperature. It must be emphasised that the predictive capability of P_{SWT} is rather surprising from a microstructural viewpoint. Obviously the effect of mechanical prehistory on the cyclic stress-strain behaviour determines the change in fatigue life that results from predeformation. Other aspects, such as surface roughening due to tensile prestraining, a different crack initiation site and a change in the dislocation arrangement of cyclic saturation, seem to have comparably small direct influence on N_f.

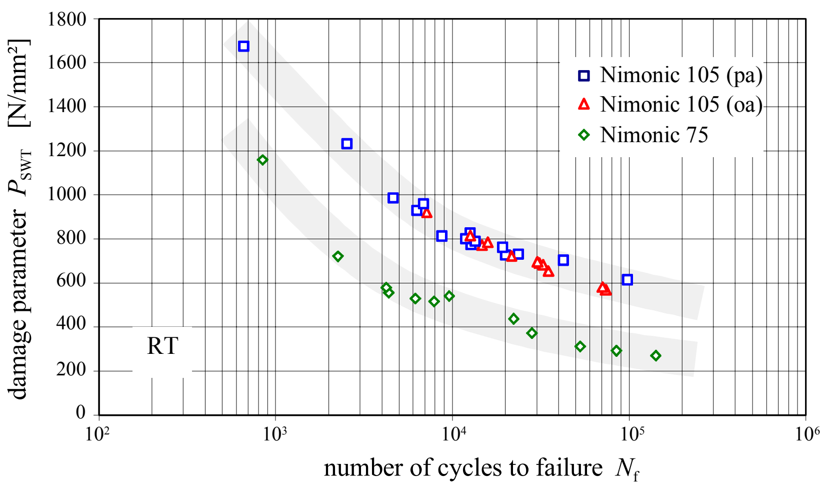

Figure 5: Description of cyclic lifetime at room temperature by means of the Smith-Watson-Topper damage parameter

The successful description of cyclic life by means of P_{SWT} allows the definition of a simple predeformation parameter S_{P_SWT}.

$$S_{P\_SWT} = 1 - \frac{P_{SWT}^{not\ predeformed}}{P_{SWT}^{predeformed}} \tag{2}$$

S_{P_SWT} approaches a value of 1, if the prehistory strongly affects P_{SWT} in such a way that P_{SWT} is tremendously increased as compared to the non-predeformed condition. A value of 0 corresponds to the situation that the prehistory does not lead to a change in the cyclic stress strain response so that the value of P_{SWT} after predeformation equals the one of the non-predeformed (reference) behaviour.

Figure 6 shows that the parameter S_{P_SWT} turned out to be very helpful for a quantitative representation of the effect of loading parameters on the prehistory dependence. As already described above, increasing temperature decreases the influence of predeformation, whereas an increasing value of the prestrain acts inversely. As a first approach, the linear relationships depicted in Figure 6 as dashed lines can be used to mathematically express these correlations. Linear relations are not obeyed as far as the effect of plastic strain amplitude and particle strengthening is concerned. However, the trends are clearly visible in corresponding representations (not shown here) that an increase of $\Delta\varepsilon_{pl}/2$ reduces the influence of predeformation and that prehistory dependence is the more pronounced the more effective the particle strengthening.

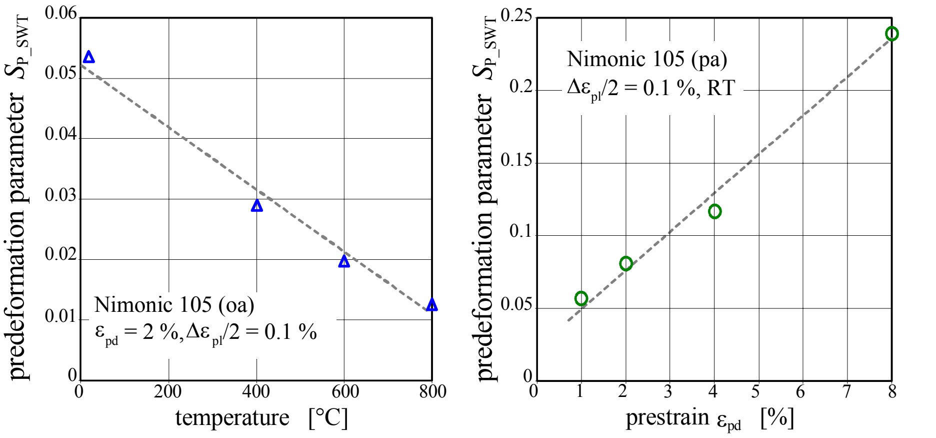

Figure 6: Effect of testing temperature (a) and value of prestrain (b) on the predeformation parameter for Nimonic 105

Since P_{SWT} works reasonably to describe the changes in cyclic life, also S_{P_SWT} is expected to be a suitable parameter for this purpose. As shown in Figure 7 for Nimonic 105, the main advantage of the application of S_{P_SWT} instead of P_{SWT} is that the correlation between the ratio of the number of cycles to failure of the non-predeformed condition $N_{f(npd)}$ to the corresponding value $N_{f(pd)}$ after predeformation (ordinate in Fig. 7) with S_{P_SWT} (abscissa) is independent of temperature. A very similar result was obtained for the particle-free alloy Nimonic 75. It should be noted that S_{P_SWT} can be both positive and negative. A negative value leads to cycle life ratios smaller than 1. That means that under the respective conditions predeformation extends cyclic life.

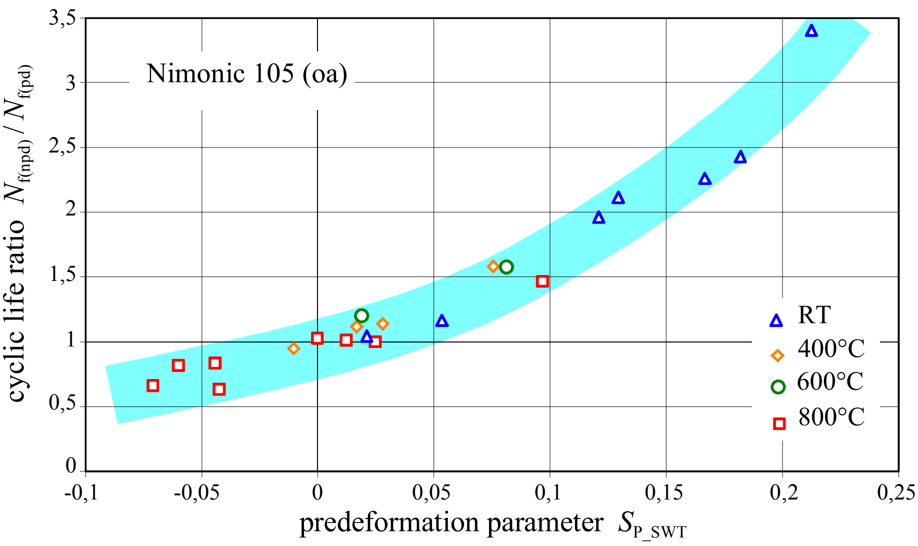

Figure 7: Description of cyclic lifetime of Nimonic 105 (over-aged) at various temperatures by means of the predeformation parameter

One reasonable application of the correlation shown in Figure 7 is the assessment of the extent of cyclic life change by prehistory. For this purpose, the corresponding value of S_{P_SWT} can be determined performing two fatigue tests at identical test parameters, one on the material in the reference (annealed) condition and one in the predeformed conditions. The tests only need to be run until cyclic saturation is established, since then P_{SWT} does not change any further (see Eqn. 1). S_{P_SWT} can easily be calculated from Eqn. 2, and the connection of S_{P_SWT} with the cyclic life ratio allows to predicted the change in cyclic life irrespective of the test temperature.

In order to define the range of applicability of the predeformation parameter S_{P_SWT}, fatigue life data obtained in an earlier study on the effect of predeformation on the room temperature fatigue behaviour of polycrystalline copper and α-brass [11] was evaluated. α-brass is known to show a very pronounced planar dislocation slip behaviour and behaves therefore microstructurally similar to Nimonic 75. This seems to be the main reason why the S_{P_SWT} concept introduced by Figure 7 applies to this material as well. However, the dislocation arrangement in copper as a wavy-slip metal depends very sensitively on the plastic strain amplitude of cyclic loading and the degree of predeformation. Dislocation cells are formed at high values of $\Delta\varepsilon_{pl}/2$, but are also prevailing after strong prestraining and subsequent cyclic deformation even at low $\Delta\varepsilon_{pl}/2$. Single-slip dislocation arrangements, such as bundle/vein structure and persistent slip bands, are restricted to small value of $\Delta\varepsilon_{pl}/2$ and very low degrees of predeformation. Taking this strong variation in dislocation arrangement into account and considering that the S_{P_SWT} parameter ignores changes in microstructure and mechanism, it is not surprising that the data of copper can not be described by a single curve in the representation of the cyclic life ratio versus S_{P_SWT}. Consequently, a prerequisite for the application of the S_{P_SWT} concept is that no fundamental changes in the microstructure takes place within the range of predeformation and cyclic loading parameters considered.

CONCLUSIONS

The main results obtained in this study on the effect of a monotonic tensile prestrain on cyclic stress-strain response and fatigue life of Nimonic 75 and Nimonic 105 (over-aged and top-aged) at temperatures ranging from room temperature up to 800°C can be summarized as follows:

- The effect of predeformation on cyclic life can be described by means of the Smith-Watson-Topper damage parameter P_{SWT} despite a change in the microstructure and the favourable crack initiation site with room-temperature tensile prestraining
- Based on P_{SWT} the predeformation parameter $S_{P\_SWT} = 1 - \frac{P_{SWT}^{not\ predeformed}}{P_{SWT}^{predeformed}}$ is introduced.
- S_{P_SWT} successfully applies to quantitatively describe the effect of cyclic loading parameters, extent of predeformation and particle strengthening on the prehistory dependence.
- S_{P_SWT} correlates with the predeformation-induced cyclic life change in an unambiguous way. This correlation is independent of the temperature of cyclic loading.
- The applicability of S_{P_SWT} is restricted to materials and conditions which do not undergo a fundamental microstructural change.

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