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EFFECT OF PLASTIC PRESTRAIN MAGNITUDE ON UNIAXIAL TENSION CREEP OF COPPER AT ELEVATED TEMPERATURES

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The effect of prior plastic deformation on creep properties such as minimum creep rate, time to rupture, duration of creep stages, and elongation at 523 and 573 K under uniaxial stress state has been determined for various tensile plastic prestrains. It has been shown that minimum creep rate, and elongation decreased as the amount of plastic prestrain increased. However, this relation was proportional to the plastic predeformation only up to $\varepsilon^p = 5\%$. A little increase of the time to rupture with the increase of plastic predeformation has been observed for specimens tested at higher temperature (573 K) in comparison to nonprestrained material. In the case of lower temperature (523 K) the lifetime decreased significantly with the increase of plastic predeformation. Predeformation also shortened the duration of primary and secondary creep stages for both temperatures considered.

1. Introduction

In practice most engineering structures or some their parts are subjected to prestrain during the lifetime. It is important from the engineering point of view to know the influence of such prestrain on different material properties at high temperatures such as minimum strain rate, ductility, lifetime, fracture and crack propagation. It has been found (cf Wilson (1973); Dyson and Rodgers (1974); Dyson et al. (1976); Marlin et al. (1980); Rees (1981); Trąmpczyński (1982); Waniewski (1983); Pandey et al. (1984); Ohashi et al. (1986); Kawai (1989); Murakami et al. (1990); Kowalewski (1991a,b); Xia and Ellyin (1993)) that plastic deformation at both room and elevated temperatures prior to creep testing has either beneficial or detrimental effect on the materials. Although the problem has been previously studied experimentally for several materials only a limited amount of available data reflects the influence of plastic predeformation on the creep process up to rupture (cf Dyson and Rodgers (1974); Dyson et al. (1976); Marlin et al. (1980); Pandey et al. (1984)). It is well known that the problem is particularly important during fabrication or assembly processes, where a number of materials used in critical elements of engineering structures may receive such cold work and as a consequence, it may change significantly their lifetime. Since the plastic prestrain of various amount may be introduced during manufacturing processes it is worthwhile to analyze the influence of the magnitude of predeformation on the creep behaviour. Up to now the amount of experimental data is insufficient to estimate exactly whether the increase or decrease of creep strengthening occurs up to a certain amount of prestrain only, or whether this creep property is in some way proportional to the amount of predeformation. Thus, in order to achieve better understanding of this problem further thorough investigations are needed.

The aim of this paper is to present the results of creep to rupture experiments carried out on the thin-walled tubular specimens of pure copper under uniaxial tension which should be helpful in analysis of the problem.

2. Details of experimental procedure

Specimens employed were thin-walled tubes with outside diameter, wall thickness and gauge length of 25, 1.5 and 40 mm, respectively (Fig.1). The material for specimens was M1E technically pure copper (manufactured according to Polish Standards) subjected to the two hours heat treatment at 673 K and subsequent furnace cooling before machining.

The experimental programme consisted of creep tests under uniaxial tension at 523 and 573 K for pure copper in the virgin state and for the same material plastically prestrained at room temperature. Prestrain values of 2.5%, 5%, 7.5% and 10% were selected in tests at 523 K, whereas tests at 573 K were carried out for testpieces prestrained up to 5% and 10%. Investigations into the effect of plastic predeformation on subsequent creep process were conducted according to the following procedure. First of all, each thin-walled tubular specimen was proportionally deformed up to a chosen value of plastic prestrain by uniaxial tension at room temperature and then unloaded, Fig.2 and Fig.3. Subsequently, each specimen was heated uniformly at the chosen test temperature for 24 h prior to testing and then was subjected to the constant stress

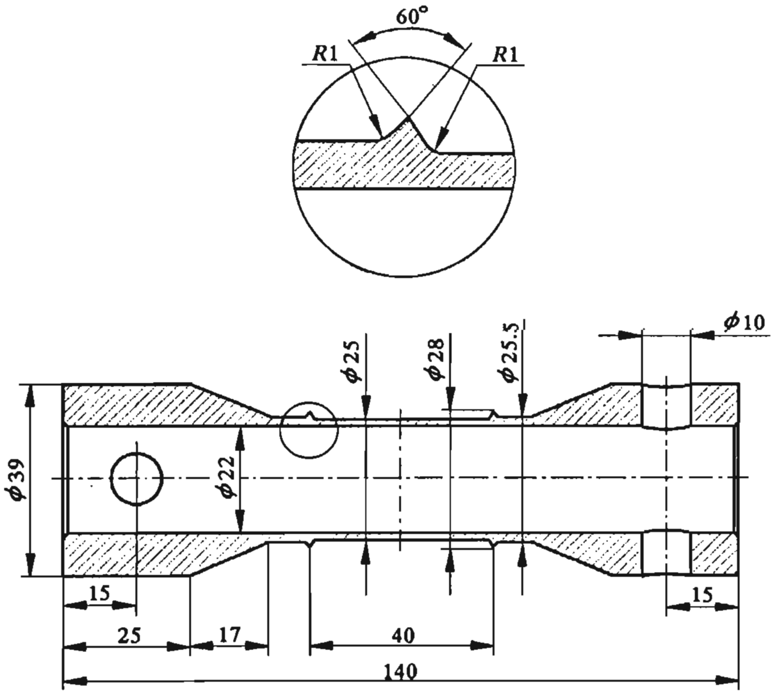

Fig. 1. Engineering drawing of the testpiece

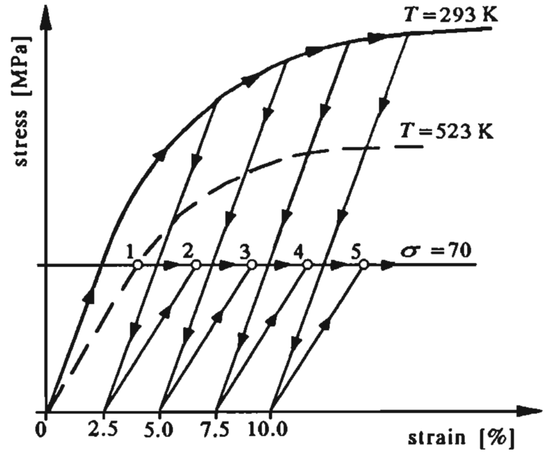

Fig. 2. Experimental programme of tests at 523 K (Bold solid line reflects schematically a part of tension characteristic at the room temperature, bold broken line illustrates schematically a part of tension characteristic at testing temperature)

level equal to 70 MPa for tests at 523 K, and 45 MPa at 573 K. Both creep stress levels were smaller than the yield point value of the material at considered temperatures. Diagrams of the experimental programme are presented in Fig.2 and Fig.3.

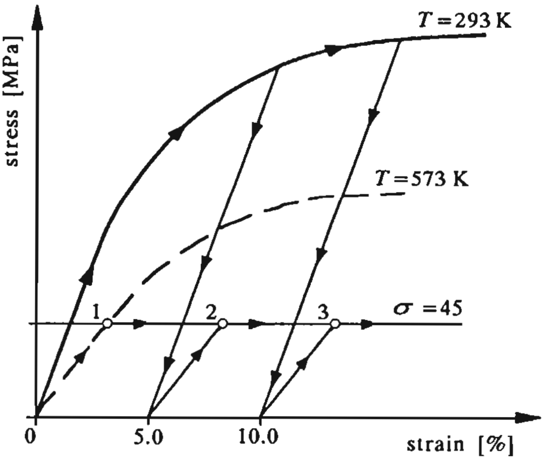

Fig. 3. Experimental programme of tests at 573 K (Bold solid line reflects schematically a part of tension characteristic at the room temperature, bold broken line illustrates schematically a part of tension characteristic at testing temperature)

Experiments were carried out with the use of biaxial creep testing machine, details of which are given by Kowalewski (1987).

The strain measurement technique used utilized the mechanical extensometer connected to the protrusions machined on the testpiece, Fig.1, to identify the gauge length over which the strain is to be measured (cf Kowalewski (1987)). These protrusions were used to transfer the displacement occuring during creep to a location outside of the high temperature furnace where the linear voltage displacement transducers could accurately measure the displacement at the ambient temperature.

3. Results and discussion

The creep curves obtained at 523 K are presented in Fig.4, whereas at 573 K in Fig.5. As clearly seen from these figures, the creep process under constant stress is generally affected by prior plastic strain at the room temperature. Cold work preceding the creep either at 523 K or at 573 K induced the

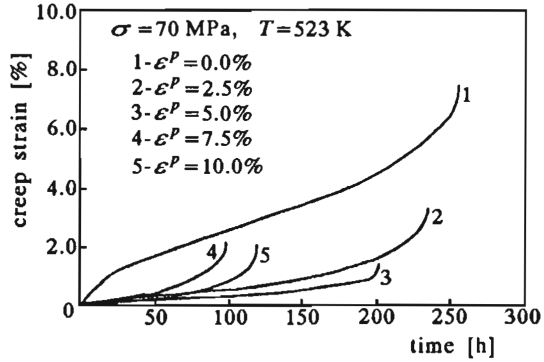

Fig. 4. Comparison of creep curves at 523 K for virgin copper and the same material plastically prestrained up to selected strain amounts

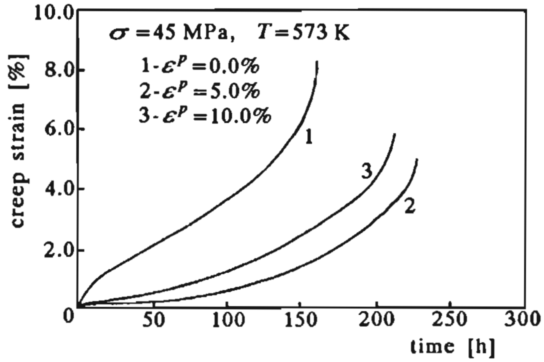

Fig. 5. Comparison of creep curves at 573 K for virgin copper and the same material plastically prestrained up to selected strain amounts

hardening effect expressed by a significant decrease in the minimum creep rate, Fig.6. Similar effect for this material was earlier observed by Trąmpczyński (1982), Waniewski (1983), and Kowalewski (1991a,b). Taking into account the recovery creep theory based on the Orowan equation in the following form

$$d\sigma = \frac{\partial \sigma}{\partial \varepsilon} d\varepsilon + \frac{\partial \sigma}{\partial t} dt \tag{3.1}$$

this is an expectable effect. According to this theory a balance between the recovery rate $\partial\sigma/\partial t$ and the rate of strain hardening $\partial\sigma/\partial\varepsilon$ produces the secondary creep rate, which can be expressed as

$$D = \frac{-\dfrac{\partial \sigma}{\partial t}}{\dfrac{\partial \sigma}{\partial \varepsilon}} \tag{3.2}$$

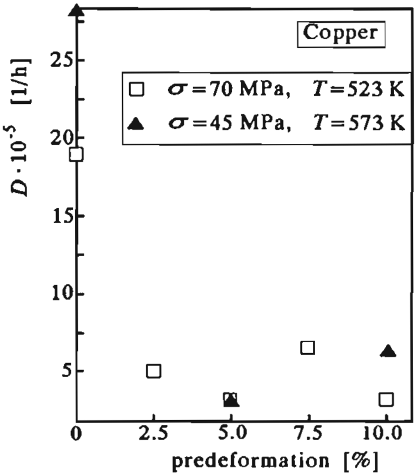

Fig. 6. Diagram of the stationary creep rate versus the amount of plastic prestrain

Plastic predeformation of a material generates dislocations, the density of which depends on the prestrain amount. So, the predeformed specimen should creep with a lower rate than the nonprestrained one. Considering tests at 523 K it is easy to note that the strain hardening effect observed was proportional to the plastic predeformation only up to 5%. Over this value the hardening effect expressed by the decrease in the secondary creep rate was also noticeable, but its amount was not proportional to the magnitude of predeformation. Such behaviour is not predicted by the recovery creep theory. In tests performed at 573 K a similar tendency was observed. Thus, it may be concluded that the tensile plastic prestrains reduce the secondary creep rate, but the magnitude of this decrease is not proportional to the amount of tensile plastic prestrain.

The results for copper tested at 523 K also show that the time to rupture, Fig.7, and elongation, Fig.4, were reduced due to the plastic prestraining. As is shown this tendency exhibits monotonical character up to the prestrains of 5%. Further variation of these parameters connected with further increasing of prior plastic deformation has rather accidental character (look at the creep curves 4 and 5 in Fig.4). The decrease of the time to rupture is relatively insignificant for tests with prestrains up to 5%, whereas for predeformations greater than 5% the change of this parameter is drastic, Fig.7.

Contrary to the creep tests of copper prestrained at 523 K, times to rupture obtained for tests at 573 K were longer than the value of this time obtained for the virgin material at the same temperature of 573 K. The reason for such

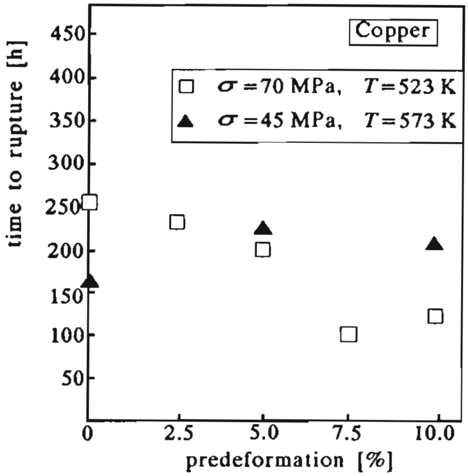

Fig. 7. Diagram of the time to rupture versus the amount of plastic prestrain

difference is presumably connected with the effect of grain size on the creep process. The process of grain size growing during the creep in the case of 573 K temperature was much more advanced than that at 523 K since this temperature is significantly closer to the recrystallization temperature of copper. From previous creep investigations it has been found (cf Kowalewski (1992)) that in comparison to fine-grained copper the coarse-grained one exhibits lower values of the minimum creep rate and longer lifetimes at the same stress level. Hence, it may be supposed that it is one of the reasons for the difference in the effect of plastic predeformation on the time to rupture during subsequent creep of copper tested at different temperatures.

At all prestrains the creep curves displayed primary, secondary, and tertiary creep behaviour, Fig.4 and Fig.5. The duration of primary and secondary periods decreased with increasing prestrain. It is interesting to note that in practice the primary creep period decreases independently of the predeformation amount, Fig.8, while the time to beginning of the tertiary creep stage decreases monotonically with increasing prestrain, Fig.9. In comparison to the material in the virgin state the amount of creep strain in primary stage decreases at all prestrains.

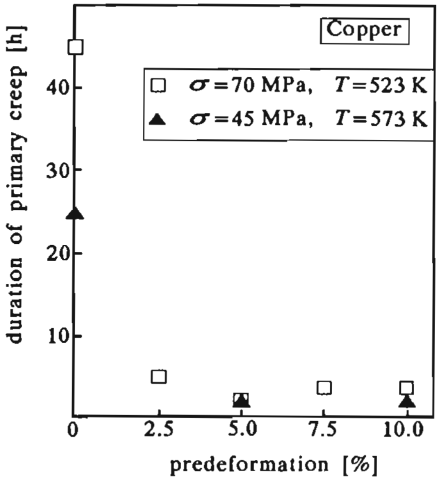

Fig. 8. Duration of the primary creep stage versus the amount of plastic prestrain

Table 1. Creep parameters for copper tested at the temperature of 523 K

	$\sigma = 70$ MPa $T = 523$ K				
	$\varepsilon^{(p)} = 0\%$	$\varepsilon^{(p)} = 2.5\%$	$\varepsilon^{(p)} = 5.0\%$	$\varepsilon^{(p)} = 7.5\%$	$\varepsilon^{(p)} = 10.0\%$
$D \cdot 10^{-5}$[1/h]	18.4	4.8	3.0	6.5	3.0
t_I [h]	45	5	2	3	3
t_{II} [h]	170	100	90	25	15
t_R [h]	254	234	200	97	121

Notation in Table

D – a steady creep rate at uniaxial tension

t_I – a duration of primary creep

t_{II} – a time to third creep period

t_R – a time to rupture.

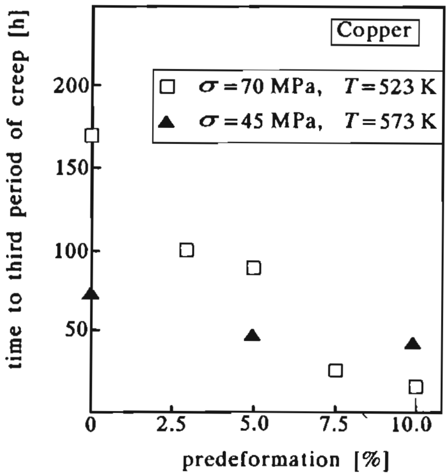

Fig. 9. Time to the third period of creep versus the amount of plastic prestrain

Table 2. Creep parameters for copper tested at the temperature of 573 K

	$\sigma = 45$ MPa $T = 573$ K		
	$\varepsilon^{(p)} = 0\%$	$\varepsilon^{(p)} = 5.0\%$	$\varepsilon^{(p)} = 10.0\%$
$D \cdot 10^{-5}$ [1/h]	28.0	3.0	6.2
t_I [h]	25	2	2
t_{II} [h]	75	45	35
t_R [h]	160	227	212

4. Conclusions

The main results stemming from this research can be summarized as follows:

- The tensile creep resistance was enhanced by plastic prestrain, which was expressed by a significant decrease in the steady creep rate. However, the amount of this effect, in the case of copper tested in this work, is not proportional to the increase of predeformation.
- The duration of the primary creep period decreases, in practice, independently of the amount of prior plastic deformation.

- The duration of secondary creep stage decreases as the magnitude of plastic prestrain increases.
- The results demonstrate that the creep fracture process can be modified by prior cold working. In the case of tested copper the creep life depending on testing temperature may either be increased or decreased to dangerously low levels.
- The amount of creep deformation for both temperatures considered was markedly reduced by the prior tensile plastic strain, yielding very low levels. Elongations of the testpieces were proportionally decreased when the magnitude of plastic prestrain increased. However, in the case of copper tested such response was limited to the value of predeformation equal to 5%.

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Wpływ wielkości wstępnej deformacji plastycznej na pełzanie miedzi przy jednoosiowym rozciąganiu w podwyższonych temperaturach

Streszczenie

W pracy określono wpływ wstępnej deformacji plastycznej, o różnej wielkości, na takie parametry pełzania przy jednoosiowym stanie naprężenia w temperaturach 523 i 573 K, jak ustalona prędkość pełzania, żywotność, długotrwałość charakterystycznych okresów pełzania oraz wartość wydłużenia przy zniszczeniu. Pokazano, że ustalona prędkość pełzania, oraz wydłużenie maleją wraz ze wzrostem wielkości wstępnej deformacji, jakkolwiek zależność ta była proporcjonalna jedynie do wartości predeformacji wynoszącej 5%. Żywotność próbek przy pełzaniu w wyższej temperaturze (573 K) nieznacznie wzrastała w porównaniu do materiału nieodkształconego, natomiast w niższej (523 K) malała wraz ze wzrostem deformacji wstępnej. Dla obu rozpatrywanych temperatur zaobserwowano efekt skrócenia zarówno pierwszego jak i drugiego okresu pełzania.

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