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The temperature dependence of the residual strength and ductility of a type-316 LN austenitic stainless-steel after prior cold work by tension and swaging

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Industrial Summary

The influence of temperature and prior cold work on the residual tensile strength and ductility of a type-316 LN austenitic stainless-steel has been studied in the temperature range 300–1123 K after prior deformation at room temperature by tension and swaging. In general, it was observed that the effect of prior cold work by different modes of deformation on the mechanical response of the material has a qualitatively common trend of increasing the strength and reducing the ductility. A structure-sensitivity parameter (the ratio of the yield strength of the prior cold-worked material to that of the as-received material at a given temperature) is proposed and found to increase with temperature and the degree of prior cold work. The additional strengthening of the structure in the temperature range up to 823 K is considered to arise due to dislocation interaction with solutes or precipitates. The decrease of the structure-sensitivity parameter above 823 K is attributed to dynamic recovery processes and/or the absence of dislocation solute interaction.

1. Introduction

Nitrogen-alloyed austenitic stainless-steel has emerged as an important structural material for liquid metal cooled fast-breeder reactors (LMFBR)

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because of its excellent high-temperature strength and corrosion resistance. An understanding of the tensile properties of structural steels subjected to prior deformation is required for the assessment of the structural integrity of certain key components of fast-breeder reactors that are put into service in the prior-cold-worked condition. Amongst the various means of strengthening metals and alloys, prior cold work at ambient temperature or warm working [1–3] are considered for obtaining improved strength. The influence of prior deformation on the creep [4–9] and low-cycle fatigue [10] behaviour of various alloys has been investigated in the past. Cold work could be deliberate, as in the case of fuel cladding to improve void swelling and creep resistance, or unintentional as that occurring during the carrying out of forming operations on components. Structural modifications due to prior cold work at room temperature govern the residual mechanical properties of the material at a given temperature. The measurement of the residual mechanical properties of the prior-cold-worked material over a wide range of temperature helps in the understanding of the different flow mechanisms that occur in the microstructure at different temperatures. The main aim of this paper is to discuss the results of the measurement of the residual strength and ductility of a type-316 LN austenitic stainless-steel in the temperature range 300–1123 K, that had been subjected previously to different levels of deformation by tension and swaging.

2. Experimental procedure

The material used in this investigation was a type-316 LN austenitic stainless-steel having the following chemical composition (wt%): C 0.021, Mn 1.74, Ni 12.0, Cr 17.0, Mo 2.4, N 0.078, S 0.002, P 0.023. The material was in plate form, of 25 mm thickness. 25 mm × 25 mm square bars were cut from the plate and machined to 16 mm diameter round bars, the axis of the bars being in the rolling direction of the original plate. These were subjected to different levels of cold work by tensile deformation and by swaging. An Instron model 1195 universal testing machine was used to introduce cold work by tension and a rotary swaging machine was used to impart cold work by swaging. In both cases the amount of cold work was calculated as the percentage reduction in cross-sectional area. The cold-worked rods were fabricated into button-head tensile specimens with a gauge length of 26 mm and a gauge diameter of 4 mm. The specimens were tested subsequently in an Instron model 1195 universal testing machine in the temperature range 300–1123 K at a nominal strain rate of 0.3×10^{-3} s^{-1}. The test temperatures were controlled to within ± 2 K. A strip chart recorder was used to record the load–elongation data.

3. Results and discussion

The temperature dependence of the strength (0.2% yield strength and ultimate tensile strength) is shown in Figs. 1 and 2 as a function of the amount of

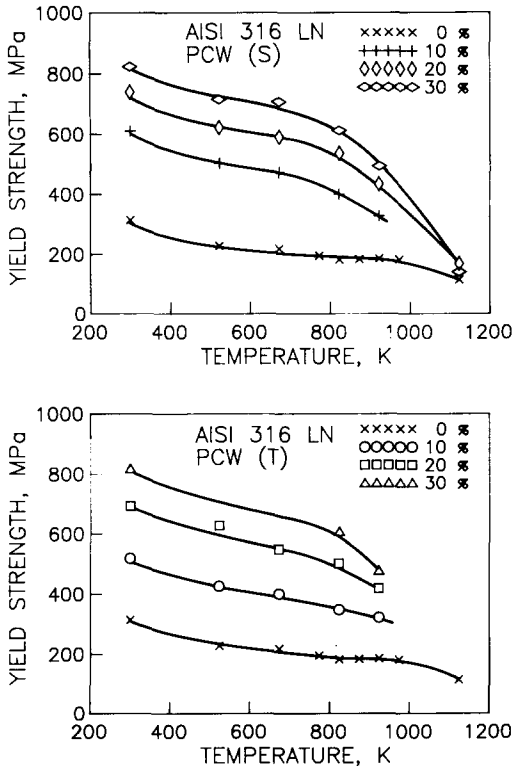

Fig. 1. Temperature dependence of the yield strength as a function of PCW: (T) PCW by tension; (S) PCW by swaging.

the prior cold work (PCW) for the two modes of deformations. The following observations can be made regarding the strength properties of the prior-deformed material with respect to the as received-material.

(1) PCW increases both the yield strength and the ultimate tensile strength at all temperatures, the increase in the yield strength being more pronounced when compared to the increase in the ultimate tensile strength.

(2) The increase in the yield strength depends on the temperature, being greater at lower temperature.

(3) Cold working by swaging leads to a greater yield strength for 10% and 20% deformation compared to the yield strength of the material that had been cold worked by tension. For 30% prior deformation, both the tensile and the swaging mode of deformation led to a 200% increase in yield strength at room temperature, this increase being maintained up to almost 823 K. Above 823 K, the increase in yield strength due to PCW is found to diminish with increase in the test temperature. For both modes of prior deformation and for different levels of PCW, the variation of strength with temperature shows a plateau or peak at an intermediate temperatures, followed by a rapid fall at higher temperatures.

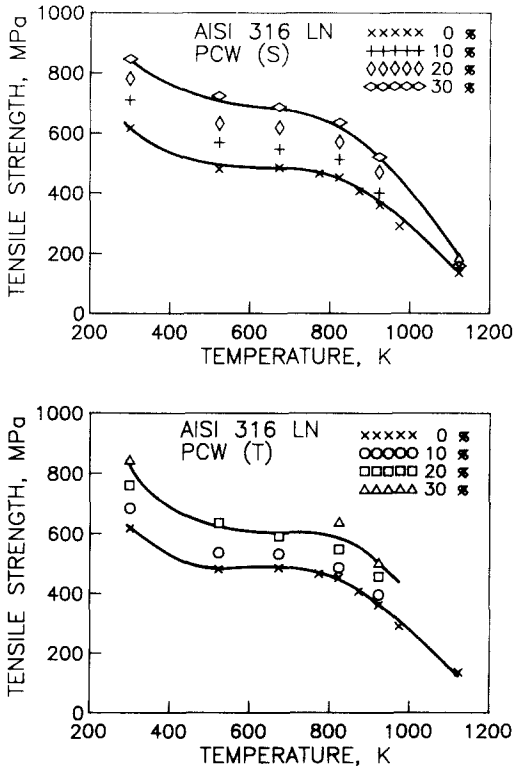

Fig. 2. Temperature dependence of the tensile strength as a function of PCW: (T) PCW by tension; (S) PCW by swaging.

Figures 3 and 4 show the temperature dependence of the engineering fracture ductility (total elongation) and the uniform elongation (elongation up to the onset of necking) at various levels of PCW for both modes of deformation. For the as-received material, the total elongation decreases initially with increase in temperature, shows a minimum in the temperature range 523–823 K and then increases with further increase in temperature, PCW by swaging and by tensile deformation producing a similar trend. For both modes of deformation, the ductility decreases with further increase in PCW. The uniform elongation shows a minimum at around 523 K and a hump at around 823 K followed by a decrease with further increase in temperature. The reduction in ductility of the cold-worked material with respect to the as-received material is more pronounced for the swaged material than it is for the material cold worked by tension, especially for the level of 10% PCW. At higher levels of PCW both tensile and swaging deformation led to generally similar values of ductility.

It is now well established that the plateau or peak in the variation of flow stress with temperature and the corresponding ductility minimum result from dynamic strain ageing (DSA) [11–18] due to dislocation solute interaction. It is

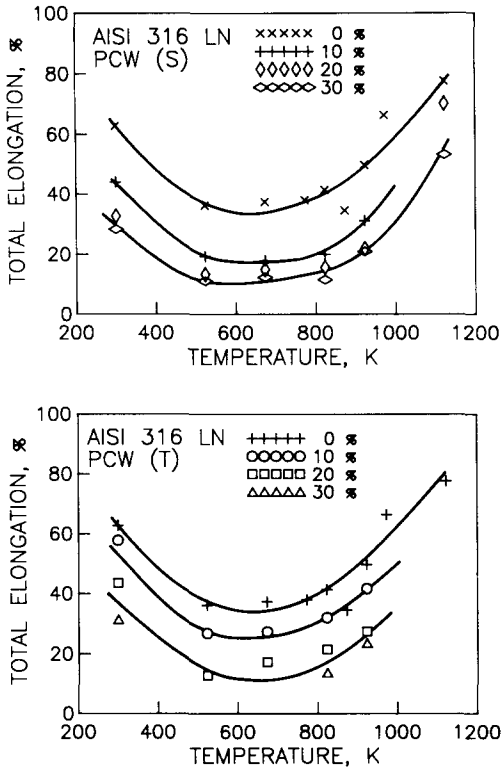

Fig. 3. Temperature dependence of the total elongation as a function of PCW: (T) PCW by tension; (S) PCW by swaging.

well known that prior deformation produces dislocation tangles, cells or subgrains, depending upon the level of cold work and the subsequent treatment. These dislocation structures act as barriers to dislocation motion and contribute significantly to the increase in strength, with consequent decrease in ductility. The yield strength of the cold-worked material is related to the flow strength of the as-received material when subjected to an identical deformation path. Hence the increase in yield strength is understandable and the yield strength of the PCW material can be taken as an indicator to assess qualitatively the strength of the structure developed by PCW. The UTS is not expected to be influenced significantly, due to the PCW involved in tensile deformation. The observed difference in strength and ductility between the tensile and the swaging mode of cold work could be attributed to the difference in the deformation history and in the substructure developed prior to tensile testing. The experimental evidence that the increase in yield strength by PCW over the as-received material is nearly constant at temperatures below 823 K is probably due to dislocation defect interaction. At temperatures above 823 K, the observed decrease could be attributed also to recovery of the cold-worked structure.

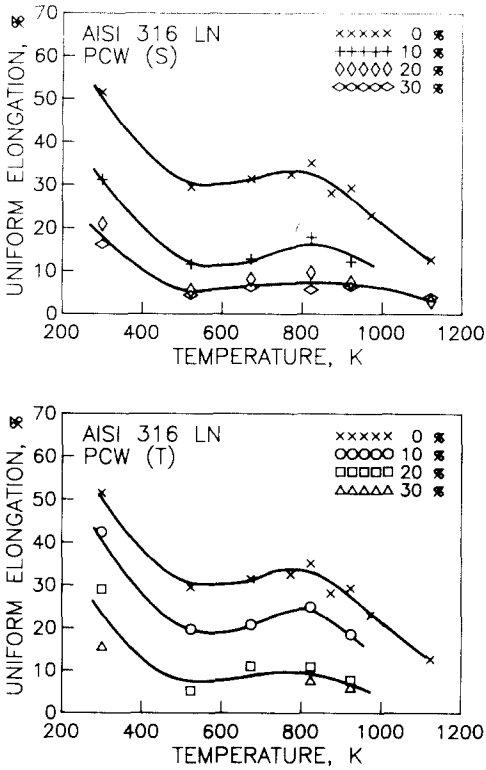

Fig. 4. Temperature dependence of the uniform elongation as a function of PCW: (T) PCW by tension; (S) PCW by swaging.

In an earlier study [19] of a type-316 stainless steel it was shown that a ductility minimum occurs at an intermediate temperature range, and that the temperature corresponding to the ductility minimum increases with increase in the grain size. The ductility minimum is due to the maximum in the rate of grain boundary sliding; at temperatures above the ductility minimum the occurrence of grain-boundary migration makes grain boundary separation a more difficult process. The decrease in ductility with increase in PCW could be attributed to ductility exhaustion due to the prior deformation. The post-necking elongation is generally constant in the temperature range 300–823 K but then increases with increase in temperature (Fig. 5). At a given temperature it is nearly independent of PCW, which indicates clearly that the exhaustion of ductility is reflected mainly in the loss of uniform elongation due to PCW.

The contribution towards strength as a result of microstructural changes due to PCW has been correlated by a parameter S, which is the ratio of the strength of the PCW material at a given temperature to the strength of the as-received material at that temperature. A quantitative correlation has been

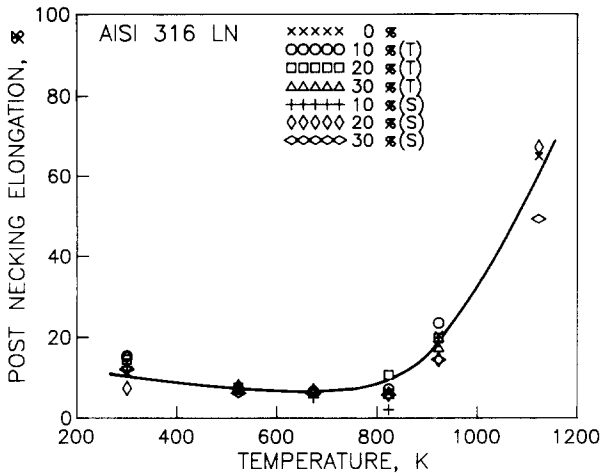

Fig. 5. Variation of post-necking elongation with temperature for different levels of PCW: (T) PCW by tension; (S) PCW by swaging.

found [20] between the parameters measuring the increase in strength (the ratio of the 0.2% yield-strength of the cold-worked to that of the as-received material) and the reduction in ductility (the ratio of the total elongation of the cold-worked to that of the as-received material) for different amounts and modes of deformation. Such parameters are dependent strongly on the damage developed in the material, either during high strain-rate deformation, as in the present case, or during slow, time-dependent deformation such as creep and low-cycle fatigue [21]. The variation of S_{YS} (yield-strength ratio) and S_{UTS} (tensile-strength ratio) with temperature are shown in Fig. 6 for different levels of PCW for the two modes of prior deformation. Parameter S_{YS} can be considered as a measure of the structure sensitivity of the initial cold-worked structure at a given temperature. S_{YS} is found to be always greater than unity and to increase with increase in temperature up to 550°C thereafter decreasing, whereas S_{UTS} is generally independent of temperature and close to unity, not showing much variation with the level of PCW. Three distinct possibilities for S_{YS} may arise.

(1) $S_{YS}=1$. This means that at the test temperature the cold-worked material has either recovered its strength completely or cold work does not have any influence; a situation where dynamic recovery takes place at the cold-working temperature.

(2) $S_{YS}<1$. This means that excessive recovery or dynamic recrystallisation of the cold-worked structure takes place at the test temperature, the material being weaker than the as-received material after PCW.

(3) $S_{YS}>1$. This means that at the test temperature the microstructure developed by PCW at RT is stronger and significant in determining the yield strength of the material.

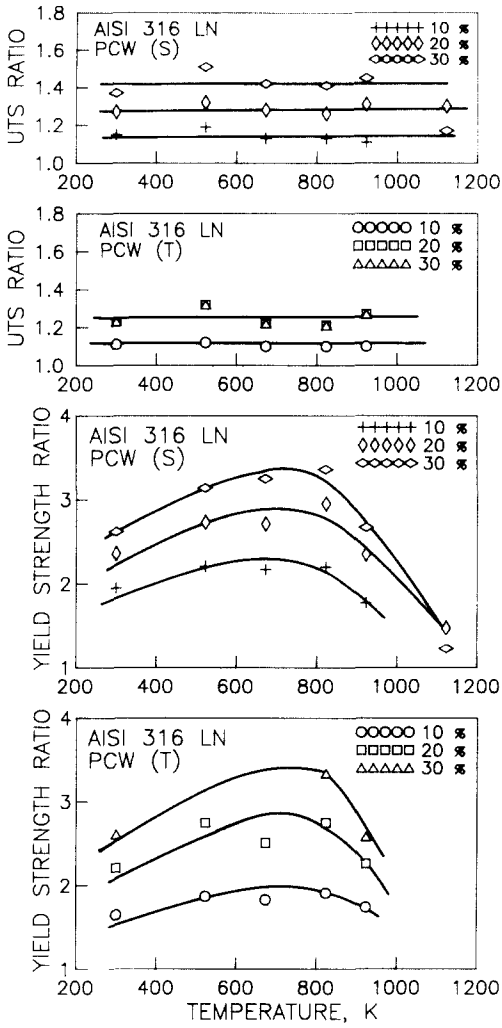

Fig. 6. Temperature dependence of the yield-strength ratio and the UTS ratio as a function of PCW: (T) PCW by tension; (S) PCW by swaging.

With increase in temperature where enhanced diffusional processes accelerate recovery of the cold-worked structure, it would normally be expected that S_{YS} would be lower than that at a lower temperature. However, in this case S_{YS} is found to increase with temperature up to 823 K, thereafter showing a tendency to decrease at higher temperature. The observed variation of increase in S_{YS} over the temperature range 300–823 K indicates that some additional strengthening takes place as the temperature is increased to keep the value of S_{YS} above that at the lower temperature. Two possibilities can be considered as factors contributing to this behaviour.

(1) Dislocation pinning by fine carbide precipitates which form at higher temperatures: this is supported by precipitation at the higher temperatures being enhanced by PCW.

(2) Dislocation being locked by solute-dislocation interaction, where interaction becomes stronger as the temperature is increased in the DSA temperature region. Point defects produced by prior deformation contribute towards this situation.

The decrease of S_{YS} above 823 K indicates the onset of substructural recovery processes, or the absence or weak solute-dislocation interaction as the temperature increases.

4. Conclusions

In general, it is observed that the effect of different modes of deformation on the mechanical response of the material have a qualitatively common trend, namely increase of the strength and reduction of the ductility. The contribution towards strength as a result of microstructural changes due to PCW is correlated to a structure-sensitivity parameter S_{YS} (the ratio of the yield strength of PCW material to that of the as-received material at a given temperature). The value of S_{YS} increases with increase in temperature up to 823 K, thereafter decreasing. The increase in S_{YS} with temperature is attributed to additional strengthening of the microstructure developed by PCW at the test temperature through fine scale precipitation or DSA, whilst the decrease in S_{YS} at higher temperature is considered to arise due to the onset of recovery.

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References

[1] D.N. Hawkins, *Mater. Technol.*, 5 (1978) 37.
[2] J.R. Knott and C.H. Symonds, *Mater. Technol.*, 3 (1976) 370.
[3] S. Venkadesan, G. Venkataraman and V. Seetharaman, *J. Mech. Work. Technol.*, 15 (1987) 81.
[4] J.M. Silcock, D. Raynor and G. Willoughby, *Met. Sci.*, 11 (1977) 551.
[5] O. Ajaja and A.J. Ardel, *Phil. Mag.*, 39A (1979) 65.
[6] J.L. Adleus, V. Guttman and V.D. Scott, *Mater. Sci. Eng.*, 44 (1980) 195.
[7] H. Burt, I.C. Elliot and B. Wilshire, *Met. Sci.*, 15 (1981) 421.
[8] C. Phaniraj, M. Nandagopal, S.L. Mannan and P. Rodriguez, in: P. Krishna Rao, M.K. Asundi and S. Gadiyar (Eds.), *Int. Conf. on Stainless Steel*, Indian Institute of Metals, Bombay, 1989, Omega, New Delhi, p. 125.
[9] J.D. Parker and B. Wilshire, *Mater. Sci. Eng.*, 43 (1980) 271.
[10] D. Douilhas, G. Cailletaux, H. Policella, D. Marquis, J. Dufailly, H.P. Lieurade, A. Ribes and E. Bolinger, *Eng. Fract. Mech.*, 21 (1985) 877.

[11] J.T. Barnby, *J. Iron Steel Inst.*, 203 (1965) 392.
[12] L.H. de Almeida and S.N. Monterio, *Proc. Second Int. Conf. on Mechanical Behaviour of Materials*, (ICM-II), August 16 20, 1976, ASM, Metal Park, OH, 1976, p. 1697.
[13] C.F. Jenkins and G.V. Smith, *Trans. AIME*, 245 (1969) 2149.
[14] V. Kutumba Rao, D.M.R. Taplin and P. Rama Rao, *Metall. Trans.*, 6A (1975) 77.
[15] D.J. Mitchell, J. Moteff and A.J. Lowell, *Acta Metall.*, 21 (1973) 1269.
[16] S.L. Mannan, K.G. Samuel and P. Rodriguez, *Trans. Indian Inst. Met.*, 36 (1983) 313.
[17] P. Rodriguez, *Bull. Mater. Sci.*, 6 (1984) 653.
[18] K.G. Samuel, S.L. Mannan and P. Rodriguez, *Acta Metall.*, 36 (1988) 2323.
[19] S.L. Mannan, K.G. Samuel and P. Rodriguez, *Mater. Sci. Eng.*, 68 (1984–85) 143.
[20] K.G. Samuel, S.L. Mannan and V.M. Radhakrishnan, *Int. J. Press. Vessel Piping*, 48 (1991) 125.
[21] C. Albertini and M. Montagnani, *Res. Mech.*, 30 (1990) 361.