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# Effect of Cr and Mo on strain ageing behaviour of low carbon steel

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ABSTRACT

This work explores the effects of Cr (0.26–0.74 wt%) and Mo (0.09–0.3 wt%) additions on the kinetics of strain ageing process in low carbon steel. The strain ageing behaviour of the steels was investigated by using tensile tests and transmission electron microscopy. The results have shown that Mo-alloyed steels undergo the same four stages of ageing as unalloyed low carbon steel, whereas Cr-alloyed steels exhibit only three stages of ageing. At the same time, the addition of Mo accelerates the ageing response, while alloying with Cr reduces the rate of strain ageing by ∼3 times in comparison with non-alloyed low carbon steel. It especially delays the offset of Stage III. This is explained by the reduction of carbon content in ferrite due to the enrichment of cementite with Cr leading to the reduction of its equilibrium solubility in ferrite.

## 1. Introduction

The strain ageing of continuously annealed low carbon steels due to the presence of carbon in solid solution during storage is a well-known problem in steel industry. It manifests itself in a change in mechanical properties (increase in strength and reduction in ductility) [1–6]. This makes difficult the subsequent forming of steel sheet, as it can lead to tearing or cracking of the sheet. It also results in a decrease in surface quality of finished products due to the appearance of stretcher-strain marks [7].

The strain ageing phenomenon is associated with the pinning of the dislocations by solute atoms [1]. It occurs only after cold deformation and is evident by reappearance of the upper yield point (UYP) and yield point elongation (YPE), often called the Lüders strain, during tensile testing. It has been shown [3,4,6] that interstitial solute levels as low as 1 wt ppm (in annealed steel) are sufficient to cause detectable strain ageing, whereas levels in excess 5–10 wt ppm cause severe strain ageing. Contrary to batch annealed steel, or continuously annealed steel which is over-aged on line, for steel strip that is annealed and hot dip coated at high temperature, as for example 55%Al–Zn metallic coated strip, the rapid cooling necessary after annealing and coating does not allow sufficient time for carbon to precipitate to equilibrium levels, resulting in the presence of ∼30–40 wt ppm carbon in solid solution [8]. This leads to very rapid strain ageing effects and with time, to quench ageing effects manifested by the precipitation of fine iron carbides.

Removal of carbon or nitrogen from solid solution is one possible solution to the problem of strain ageing. This approach is successfully applied to steels with very low total carbon levels by alloying with Ti, Nb or V to form interstitial-free steels, in which practically all of the interstitial solutes are combined as stable particles [4]. However, due to the need for vacuum degassing and additional alloying, there is a significant cost increase in the production of interstitial-free steels compared to low carbon steels. In this work we explore the possibility of delaying strain ageing in continuously annealed low carbon steel by addition less expensive carbide-forming elements, such as Cr or Mo.

## 2. Experimental

A commercial low carbon steel (G300) and experimental steels alloyed with Cr or Mo were used in this work. Their compositions are given in Table 1. Laboratory simulation of industrial processing including hot rolling, coiling, cold rolling and annealing was carried out and tensile samples were machined. Hot rolling (reheating to 1200 °C for 30 min, 2 passes, 40% reduction each, finish rolling temperature ∼900 °C, water spray cooling at 20 K/s) and cold rolling (82% total reduction) were performed by using a laboratory rolling mill at Deakin University. Coiling was simulated by placing the hot rolled material into a Quality Heat fluidized bed furnace at 660 °C. Before cold rolling the plates were straightened in a 40 ton press at Plate and Steel Industries, Braeside, then surface ground to 2.6 mm

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**Table 1**
Compositions of studied steels, wt%.

| Steel | C | N | Mn | Al | S | P | Si | Ni | Cr | Cu | Mo |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lab. G300 lower/higher | 0.06/0.07 | 0.0025/0.0035 | 0.2/0.22 | 0.035/0.04 | 0.008/0.010 | –/0.016 | –/0.002 | 0.02/0.025 | 0.02 | 0.02/0.025 | – |
| 0.09Mo | 0.058 | 0.0032 | 0.29 | 0.036 | 0.0050 | 0.0044 | 0.030 | 0.011 | 0.036 | 0.008 | 0.094 |
| 0.18Mo | 0.063 | 0.0026 | 0.20 | 0.054 | 0.0050 | 0.0050 | 0.025 | <0.01 | 0.025 | 0.009 | 0.180 |
| 0.30Mo | 0.064 | 0.0026 | 0.21 | 0.040 | 0.0044 | 0.0050 | 0.024 | 0.018 | 0.023 | 0.010 | 0.300 |
| 0.26Cr | 0.064 | 0.0025 | 0.20 | 0.060 | 0.0050 | 0.0060 | 0.024 | 0.010 | 0.26 | 0.009 | 0.020 |
| 0.52Cr | 0.064 | 0.0026 | 0.22 | 0.044 | 0.0040 | 0.0050 | 0.026 | 0.020 | 0.52 | 0.008 | 0.004 |
| 0.74Cr | 0.064 | 0.0028 | 0.21 | 0.047 | 0.0045 | 0.0050 | 0.024 | 0.015 | 0.74 | 0.007 | 0.002 |

thickness to remove the scaled and decarburized surface layer. Simulation of rapid annealing was carried out after cold rolling, in the same furnace at 705 °C. To quantify the ageing behaviour of the steels, pre-straining of the steel beyond the Lüders strain was employed (12%). This was followed by artificial ageing in an oil bath at 94 °C for periods from 5 s to 1 day. This temperature was chosen so that 1 min of ageing would correspond to approximately 1 day at ambient temperature. Steel samples were kept in a freezer all the time when not in use to minimise ambient ageing.

Tensile tests were performed on a 100 kN capacity screw-driven Instron tensile testing machine with a 25 mm gauge extensometer and a 5 kN load cell. A minimum of three tensile specimens were tested for each ageing time. The various tensile parameters were determined from the resulting stress–strain curves.

The microstructures of steels after coiling and after various ageing times were studied by transmission electron microscopy. Thin foils were prepared by electropolishing on a twin-jet Struers Tenupol-5 with a solution of 5% perchloric in methanol, at −25 °C to −30 °C. Examination of foils was performed with a Philips CM20 analytical transmission electron microscope operated at 200 kV and equipped with an Oxford Microanalysis Group, Model 6767 energy dispersive X-ray spectrometer (EDXS).

## 3. Results

### 3.1. Mechanical behaviour

The representative stress–strain curves are shown in Fig. 1. With increased alloying content from 0.09 to 0.3% Mo, the strength has increased whereas the total elongation (TE) has decreased (cf. Fig. 1a and b). Changes in Cr additions did not have such a pronounced effect on strength, but a reduction in total elongation was observed with increase in Cr content. Longer ageing times led to appearance of yield point on the stress–strain curves, a slight increase in strength and a pronounced decrease in elongation. At long ageing times a pronounced yield point extension (YPE) become a characteristic feature of the stress–strain curve. However, the upper yield point (UEP) was not clearly detectable on all stress–strain curves and the lower yield point (LYP) was used as one of the characteristics hereafter. Ageing has also an affect on

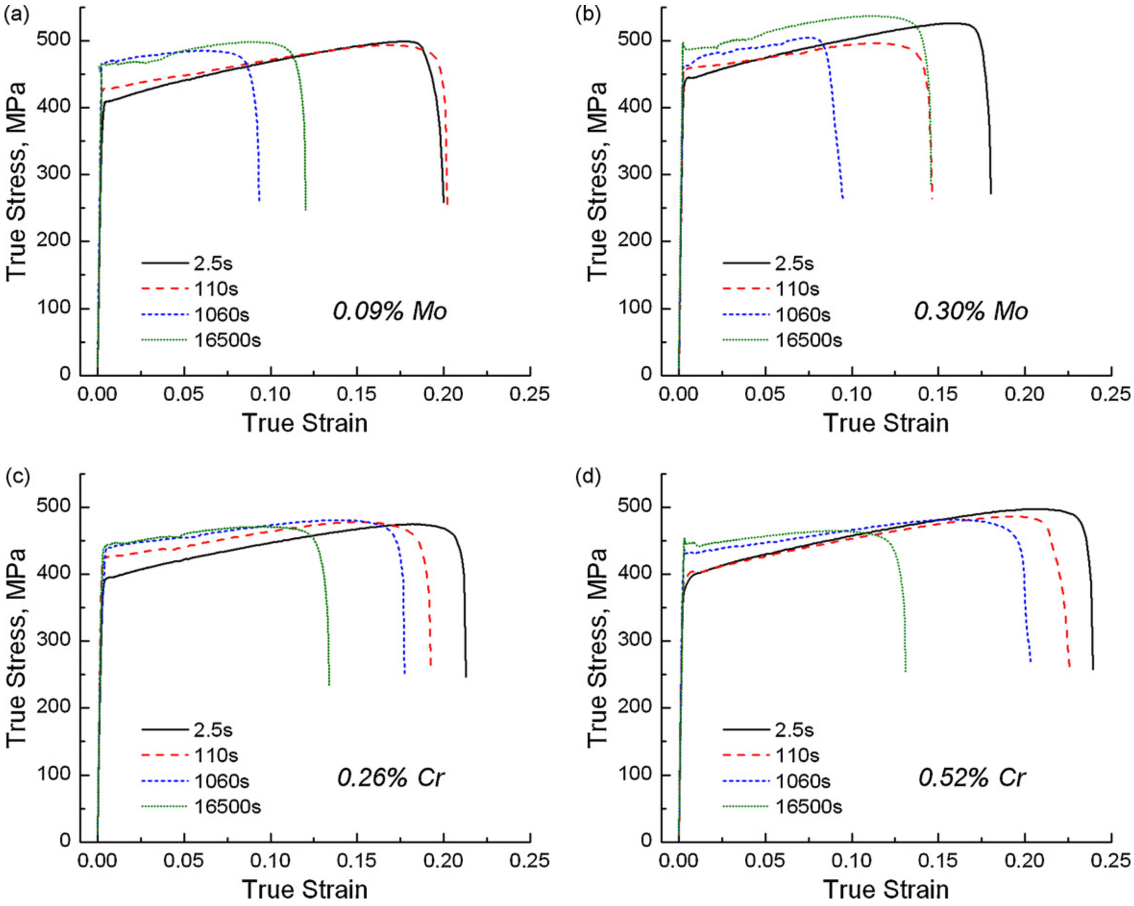

**Fig. 1.** Representative stress–strain curves of selected steels and ageing times: (a) 0.09Mo, (b) 0.3Mo, (c) 0.26Cr and (d) 0.52Cr steels.