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M. Spezzapria[1], E. Beridze[2], M. Breda[1], S. Bruschi[1], I. Calliari[1], C. Gennari[1], M. Forzan[1], F. Michieletto[1]

[1] Department of Industrial Engineering (DII), University of Padova, via Gradenigo 6/A, 35131, Padova - Italy
[2] Automation of Electric Technological Installations, Novosibirsk State Tech. Univ., Karl Marx av. 20, 630092, Novosibirsk - Russia

Corresponding author: michele.forzan@dii.unipd.it

Abstract
In many modern methods of metal processing, the materials are softened by Joule effect induced by electric current; in this way, the formability is enhanced and especially the flow stress is significantly reduced. In addition, when electric current is involved, changes in other aspects have been observed, including rebound, improved elongation and microstructural features, depending on materials and microstructures. Electric current was found to affect the flow stress on the basis of the so-called Electro-Plastic Effect (EPE), enhancing the material flow properties and especially its formability.

Key words : Electroplastic Effect, Ferritic Stainless Steel, Metal Forming, Electrically Assisted Manufacturing.

Introduction

The realization of final and intermediate products frequently requires bulk deformation stages, which are commonly accomplished in the hot-working temperature range or through cold-working steps followed by annealing treatments (incremental forming). An alternative method developed for materials forming is represented by Electrically Assisted Manufacturing (EAM), a fabrication technique based on the Electro-Plastic Effect (EPE) induced by the electric current on the material flow properties [1-8]. Several studies have pointed out the real effectiveness of this method, especially in forging, allowing an enhanced material formability by reducing the required stresses and improving the strains at rupture [1-8-9]. However, not all the examined materials have exhibited advantageous influences upon current application; moreover, it must be noticed that EPE may be hindered by the unavoidable rise in temperature as a consequence of the Joule heating.

The effect of electricity within materials has been object of several studies in the past years [1-2-8-9-10-11], leading to the development of theoretical and experimental relationship explaining EPE during plastic deformation. Three main mechanisms were found to induce EPE in the materials – localized resistive heating, electron-induced kinetic energy (electron-wind force) and the presence of an additional quantity of electrons in the material – facilitating dislocations motion within crystal lattices and resulting in an enhancement in materials workability [3,4, 8].

In metals, EPE was found to be more significant in BCC materials respect to FCC ones [4], even though a recent work by Salandro et al. [3] has pointed out that any relationship between crystal structure and a current threshold seems to not exist. Many metals were found to be positively influenced by electricity during deformation, but the occurring of EPE was frequently evaluated by measuring the reduction in flow stress at a fixed strain, without bringing the specimens to fracture and without separating the thermal contribution induced by the Joule effect. In a previous work by the authors [7], the presence of EPE in uniaxial tension has been investigated on an AISI 316L austenitic stainless steel, but any favourable variations in material properties respect room-temperature and thermal tests were not observed.

In this work, the results concerning the study of EPE on an AISI 430 ferritic stainless steel in tensile deformation are presented. The material was strained in uniaxial tension applying continuous current and in thermal chamber at the same temperature in order to separate the current effect from the heating one.

Materials and Methods

A sheet of AISI 430 ferritic stainless steel has been used, it was preliminary examined by means of a Leica DMRE Optical Microscope after chemical etching (solution composed of 75% aqua regia in ethanol), for microstructural characterization in the Rolling Direction (RD).

All samples were tested along RD on a MTS uniaxial tensile machine in strain-controlled conditions adopting a strain-rate of 10^{-1} s^{-1} (E-01). The tensile tests were conducted in thermal and current regimes, and a proper tooling setup was developed in order to avoid interferences between machine and specimen upon current application. Moreover, a cooling device aimed to limit specimens heating was employed.

An electrical DC-current power supply was adopted for continuous electric current application, and the related rise in temperature was monitored using a laser pyrometer (accuracy of ±0.5°C), in order to reproduce thermal tensile tests for the separation of temperature-related effects to those induced by current.

Results and Discussions

One of the most critical aspect in EPE tests is the separation of the electroplastic effect from the temperature dependence of the flow stress. In fact, the heat generated in the samples is strongly correlated to the material resistivity, since it is induced by the Joule effect, but also depends on the thermal conductivity of the material. In the case of AISI 430, the high electrical resistivity, the low thermal conductivity and the type of cooling device did not allow the use of high current densities without increasing the temperature exceeding the cold-working regime. For this reason, the maximum current density reached in this work has been set to 21 A/mm^2.

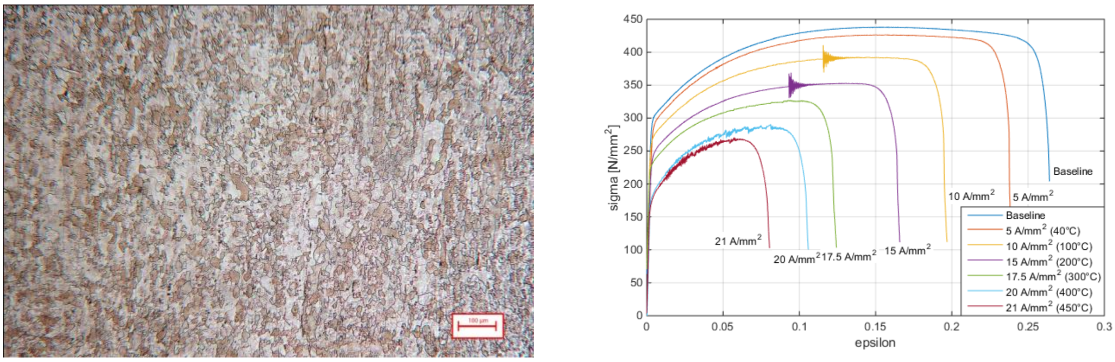

Fig. 1: Microstructure of the base material, RD is vertical (LH) and engineering curves in current regime (RH).

The as-received steel was constituted of fine ferritic grains roughly oriented toward RD, denoting a partial annealing performed after the forming operations (Fig. 1). The material was tested along RD, and the tensile test results as a function of the applied current density are reported in Fig.1, together with the reached temperatures. Electricity caused an unavoidable temperature rise – partially limited by the cooling device – that modified the material mechanical response by reducing the elongation at rupture and by lowering the Ultimate Tensile Strength (UTS). Respect to the base material curve (baseline), any enhancement in formability was not observed and the employed current densities caused a progressive reduction in mechanical properties. Therefore, owing to not negligible workpieces heating, EPE cannot be clearly observed by solely consider the test performed in current regime.

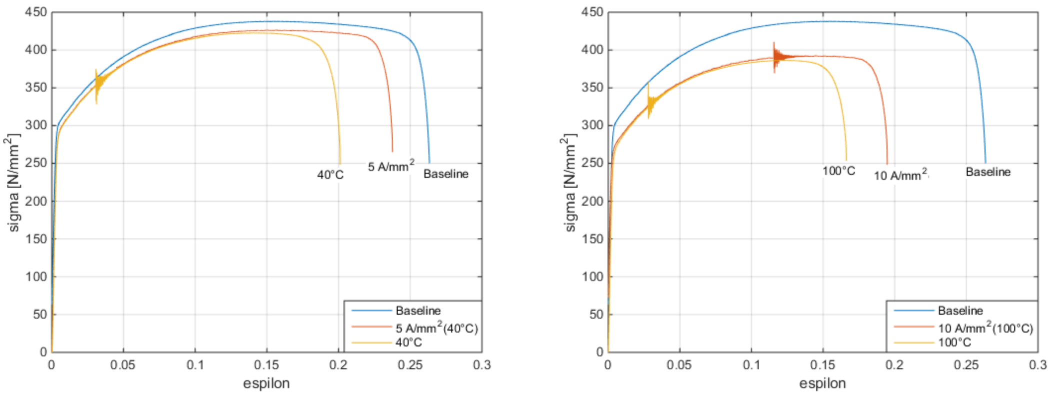

Fig. 2: Comparison among the baseline and the engineering curves obtained in current and thermal regime.

In the present experimental study, the separation of the electrical contribution from the thermal one was achieved by reproducing thermal tests at the temperatures recorded upon current application and by comparing the relative variations of total elongation and UTS respect to the baseline (relative strain and relative UTS). Two examples of thermal and current stress/strain curves are reported in fig.2: the differences of the material behaviour respect to the baseline are clearly evident. Here, by comparing thermal and electrical results, it can be noticed that electricity acted on the material properties by mainly influencing the elongation at rupture, whereas UTS was not substantially altered; in any case, the flow properties were always reduced if compared to the baseline. As can be seen from Fig.3, where relative strain and UTS are plotted against the registered temperature, this behaviour was observed in the entire experimental current density range, denoting an effective contribution of electricity in improving formability of the steel under study. However, this enhancement was reduced by applying increased current densities, since important thermal contributions in current regime were not completely avoided by the employed cooling device.

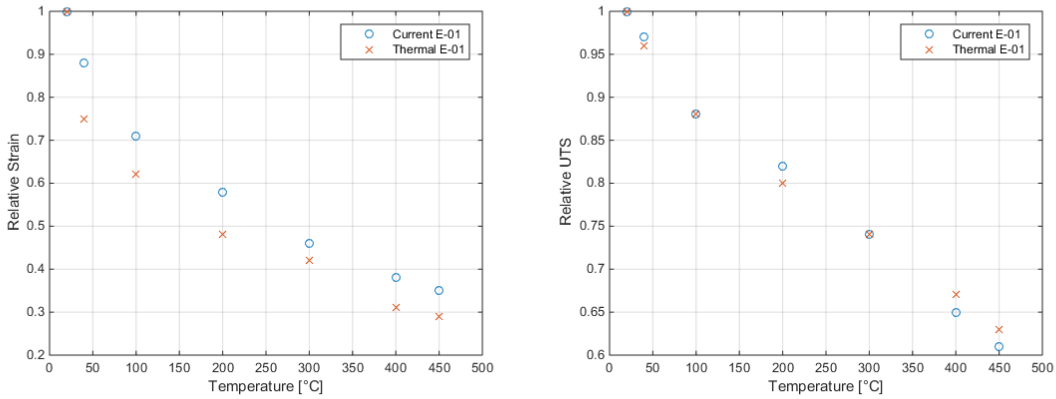

Fig. 3: Relative variations of engineering strain (LH) and UTS (RH) against the testing temperature.

Conclusions

In the present work, an experimental investigation of EPE on AISI 430 ferritic stainless steel has been presented. In the considered steel, the application of electric current from 5 to 21 A/mm^2 during uniaxial tensile deformation reduced the mechanical properties respect to the room-temperature test; however, an improvement in strain at rupture respect to the thermal counterparts was observed, whereas no noticeable effects on UTS were revealed.

A similar experimental study on an AISI 316L austenitic stainless has been recently performed by the authors [7], employing the same current densities and the same cooling device, and a reduction of the mechanical properties respect to the thermal tests has been observed as the current density was increased. Therefore, considering the same electrical resistivity for the two stainless steels grades, the enhanced response of AISI 430 can be ascribed to its different crystal structure, as also noted by Liu et al. [4]. Nevertheless, in both cases, the materials formability was always reduced respect to the baselines, making electricity in continuous regime not effective for AISI 430 as for other metals such as titanium or aluminium [9].

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