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On the connections between plasticity parameters and electrical conductivities for austenitic, ferritic, and semi-austenitic stainless steels

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ABSTRACT

This paper focuses on cross-property connections between plasticity parameters (yield limit and hardening coefficient) and electrical conductivity of stainless steels. Comparative analysis of such connections is done for four materials that differ by their microstructure and chemical content. The possibility of cross-property connection is provided by the fact that both plasticity parameters and electrical conductivity are governed by the same microstructural parameter, which is the dislocations density. The cross-property connections are obtained in explicit analytical form. Experimental observations are in good agreement with theoretical results for three of the considered materials (ferritic and austenitic steels). Behavior of semi-austenitic low carbon steel 17-7 PH, however, is completely different, that can be explained by the specific character of its microstructure. The results can be used for development of a new methodology to estimate mechanical performance of austenitic and ferritic stainless steels with high carbon content.

1. Introduction

The present research is motivated by the needs of pipe-line industry, where increasing the pipelines' life, governed by the development of various defects, is one of the main challenges. The monitoring and control of microstructure changes - formation and development of dislocations, foreign particles, cracks etc. - during working life of the structural elements is still an open problem.

The main material used to construct pipelines is stainless steel. Changes in material microstructure depend mostly on pipelines' installation type. In the case of offshore pipelining, pipelines are affected by corrosion, so the cathode's protection is usually used to control such corrosion. In the case of onshore pipelining (above-ground), pipelines are subjected to thermal fatigue that yields the increase in dislocation density. The latter, in turn, leads to change in the macroscopic residual stresses (Revie, 2015) and increase in the electrical resistivity (Watts, 1988a, 1988b).

In the present paper, we provide a comparative analysis of mechanical and electrical behavior of four stainless steels – semi-austenitic stainless steel 17-7 PH, ferritic stainless steels 430 and austenitic stainless steels 302 and 310 - typically used as construction material in pipelines' industry,. These stainless steels differ from each other by microstructure and chemical content – most importantly the carbon content which governs, in particular, the change in the yield limit during the cyclic plasticity process (Brown, 1977; Seeger, 1958). We also propose, a methodology to control changes in the yield limit and

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hardening coefficient of metals using electrical conductivity measurements. The possibility of such an approach is based on the fact that these parameters are affected by the same microstructural parameter, which is the dislocation density (note that the effect of the dislocation density on the said properties has been studied in literature, mostly, unconnectedly).

Dislocation density is defined as the number of dislocation lines crossing the unit area (Seeger, 1980). This parameter determines the character of plastic deformation of metals (Honeycombe, 1984; Kuhlmann-Wilsdorf, 1989; Seeger, 1958). When a metal is subjected to plastic deformation, the stress needed to endure the deformation increases with strain growth, i.e. the yield stress increases. This occurrence can be called as work hardening (Clarebrough & Hargreaves,1959) and its nature used to be a prominent problem, in the study of the crystals' plasticity, starting from the earliest work in this field. After all, substantive progress has been achieved since the entity of dislocations and the prevailing role in plastic deformation have been elucidated. Review studies for experimental and theoretical results was made by Cottrell (1949) and (1953a). He, also indicated (Cottrell, 1953b) that work hardening embraces the group behavior of massive number of dislocations rather than the behavior of isolated dislocations.

Since 1960 s different aspects of the relation between the dislocation density and electrical conductivity have been discussed. It has been shown that the obtained dislocations' resistivity for simple metals are harmonic according to the occurrence of resonances in the scattering near the Fermi surface (Brown, 1967a) and it can be expected that resonance happens somewhere in the conduction band (Brown, 1967b). Watts (1987) suggested that if the dominant conduction electron scattering takes place in the core regions of dislocations, then it is essential to include crystalline structure in the scattering model – otherwise, the measured degree of isotropy of the resistivity cannot be accounted for.

To the best of our knowledge, the first attempt to relate plastic yield limits to the electrical conductivity of metals was done by Bell, Latkowski, and Willoughby (1966), who showed how electrical conductivity of indium antimonite single crystal changes due to plastic bending. Actually, it was the first observation of the cross-property connection between the yield limit and electrical properties of metals. Generally, cross-property connections for heterogeneous materials belong to the fundamental problems of engineering science and physics. They relate changes in different physical properties caused by the presence of certain microstructure. Their practical usefulness lies in the fact that one physical property (say, electrical conductivity) may be easier to measure than the other. Cross-property connections have been discussed in literature for about half a century. Most of them had a character of qualitative observations. First quantitative theoretical results on cross-property connections appeared in the classical work of Bristow (1960), who derived explicit elasticity-conductivity connection for a micro-cracked material in the isotropic case of random crack orientations and low crack density. Levin (1967) interrelated the effective bulk modulus and the effective thermal expansion coefficient of a general two phase isotropic composite. Milton (1981) established cross-property bounds for the transport and the optical constants of isotropic composites. Similar bounds for the electrical and the magnetic properties were given by Cherkaev and Gibiansky (1992). The general approach to establish various cross-property correlations was outlined by Milton (1996). The conductivity-elasticity cross-property bounds have been derived in works of Berryman and Milton (1988) and Gibiansky and Torquato (1995, 1996a, 1996b). Sevostianov and Kachanov (see their review 2009 for details) established approximate cross-property connections between elastic and conductive properties of heterogeneous materials. They also shown connections between two different physical properties can be established if and only if these properties are governed by the same (or similar) microstructural parameter (Kachanov & Sevostianov, 2005). This approach has been used to connect yield limit and electrical conductivity in the papers of Dominguez and Sevostianov (2011), Omari and Sevostianov (2013) and Omari, Balázs, and Sevostianov (2014). In these works, however, the authors did not compare different materials and did not study effect of any other parameters (like carbon content or original microstructure, for example). We do it in the present work. We used the approach developed by Dominguez and Sevostianov (2011) and Omari and Sevostianov (2013) for quasi-static loading of stainless steel specimens.

2. Experimental procedure

We examine, four types of stainless steels: semi-austenitic 17-7 PH, austenitic 310, ferritic 430, and austenitic 302 (see Table 1 for their chemical content and material properties) and follow the approach of Dominguez and Sevostianov (2011) and Omari and Sevostianov (2013). For each type of stainless steel, six specimens were studied.

2.1. Specimens preparation

A water jet cutting with abrasive particles (see Fig. 1) was used to cut the different stainless steel specimens, in order to avoid any changes in microstructure and mechanical properties. This method allows one to cut the specimens without deforming or altering intrinsic properties. In addition, the need post-processing operations are mostly eliminated (Lorincz, 2009). The specimens were cut according to ASTM standards as shown is Fig. 2.

2.2. Cyclic plasticity tests

Mechanical tests have been performed according to ISO 6892 standards using Instron 5582 testing machine and Bluehill software. The applied extension rate was 500 N/min, which is in the range of quasi-static loading (Dominguez & Sevostianov, 2011). The loading-unloading process were repeated four times on each specimen to follow conditions of cyclic plasticity.