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Can Young's modulus of metallic alloys change with plastic deformation?

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Abstract. The information in the basic references about the relation between elastic constants and particularly Young's modulus (E) behavior and plastic deformation indicates that this parameter is constant or almost constant. At the beginning of the XX century several authors indicated that E of some metals decreased when cold deformation increased and detected reductions up to 15% in steels, aluminum, copper, brass... In the last years this behavior is taking into account during the finite-element analysis of sheet metal stamping or other plastic deformation processes. This work includes an extensive review of papers of our research team and of other authors related with the behavior of Young's modulus during plastic deformation of some metallic alloys. This parameter can diminish up to 10% by plastic deformation (tension test) in iron, aluminum, and stainless steel (UNS S 30403) but remains practically unaltered in aluminum alloys deformed before or after aging. Results of Young's modulus in nanostructured copper and copper alloys determined by ultrasonic technique are also presented. Additional results of Young's modulus of UNS G10180 and UNS G10430 steels measured during loading and unloading steps in tension test are also included. High differences in the E values were detected between both steps.

Introduction

The available information shows that elastic constants in metals can change with alloying, temperature and crystallographic orientation. With respect to plastic deformation, and thermal or termomechanic treatments the information indicates that these parameters are constant or almost constant. However, several researchers have been determined the behavior of elastic constants and particularly Young's modulus (E) with the described treatments [1]. Reductions up to 15% in iron, steels, aluminum, copper and so on have been detected. During decades these changes have not been taken into account in design, but in the last years the knowledge of this behavior is being very important during the finite-element analysis of sheet metal stamping or other plastic deformation processes [2,3]. The objective of this work is to summarize results obtained by our research team, but also of other authors, about the behavior of Young's modulus versus plastic deformation in iron, stainless steel, aluminum and aluminum alloys. Results obtained on Young's modulus of nanostructured copper, and copper alloys obtained by mechanical alloying, determined by ultrasonic technique are also presented. Additional results of Young's modulus of UNS G10180 and UNS G10430 steels measured during loading and unloading steps in tension test are also included.

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Young's modulus behavior with plastic deformation in metallic alloys

Yamaguchi et al [4] studied the effect of plastic deformation in sheets of low carbon steel and stainless steel, in biaxial deformation conditions. These authors detected a decrease of E in these materials with increasing plastic strain. It was confirmed that Young's modulus of the low carbon steel sheet recovered the initial value of undeformed material by a subsequent annealing. In the case of the low carbon steel E varied from 215 GPa (0% strain) to 200 GPa (for 10% strain) and 195 GPa (for 15% strain). The decrease level was of 9,3% with respect to the original material.

Benito et al [5] determined changes of Young's modulus of polycrystalline Armco iron deformed by cold rolling. Values of this parameter were determined by tension test using electrical-resistance strain gauges glued on the surface of the specimen. Fig. 1 includes the values obtained. The parameter E decreases in the first step of deformation to 193 GPa when iron is deformed aroung 20% reduction and then increases with successive cold working to 212 GPa for 60% reduction. Recrystallization over the sample with 20% cold rolled lead to obtain the initial values of E. In this work this behavior was not attributed to the residual stresses nor texture changes, but was indicated that it can be related with the dislocation distribution in all cases. Other work developed by Benito et al [1] present results of changes of E of cold deformed pure iron by tensile test. Strain was determined as previously described [5]. Results obtained are shown in Fig. 2.

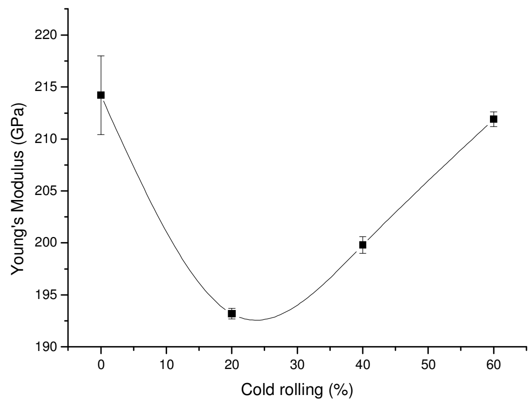

Figure 1. Young's modulus vs. plastic deformation in cold rolled iron

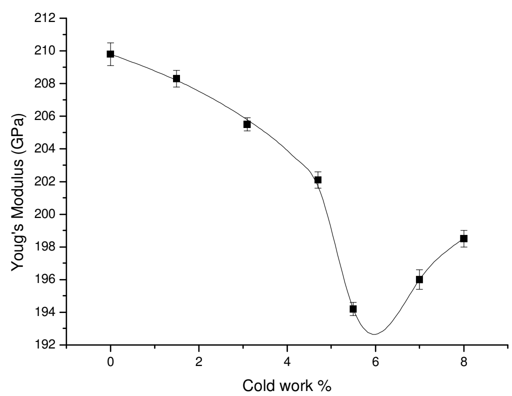

Figure 2. Young's modulus vs. plastic deformation in iron by tensile test

E decreases in the first step of deformation from 210 GPa (0% strain) to 194 GPa (5.5% strain) and then recovers to 198 GPa (9% strain). The diminution of E along the deformation process studied cannot be attributed to residual stresses nor textures. There is a close connection between the dislocation structure developed with deformation and the behavior of E.

Morestin et al [6] indicated that for different steels used in stamping processes, Young's modulus decreased 4-5% from the initial values (determined by tension test). In one of these steels, E decreased from 203 GPa to 194 GPa (4% strain) and then this value remains constant in the range between 4 and 11% strain.

Jorba et al [7] determined that Young's modulus in an AISI 304 stainless steel diminishes from 200 GPa to 185 GPa when this material is elongated 4.4% (tension test), increases to 194 GPa for 6% deformation and then decreases again achieving 170 GPa (30% deformation). This last behavior should be associated with the transformation induced plasticity of austenite (detected by X ray diffraction). Table 1 presents results obtained in the AISI 304 stainless steel.

Lucena et al. [8] studied the variation in the Young's modulus of AA 1050 (>99.5% Al) with cold plastic deformation (tension test). The experimental data was processed according to the ASTM E-111 standard. Young's modulus decreased from 69 GPa (initial material) to 63 GPa (2.5% strain), then increased to 65% (6% strain) and finally stabilized to 66 GPa (13% strain). These results were recently confirmed using the ultrasonic transmission-reception method [9].

Table 1. Young's modulus of AISI 304 stainless steel cold deformed by tensile test.

Cold work %	0	2.5	3.3	4.4	5.0	6.0	7.5	11.5	14	30
E (GPa)	200 ±1.5	193 ±4.0	194 ±1.5	185 ±1.5	187 ±0.2	194 ±2.0	189 ±2.0	187 ±2.0	184 ±2.5	170 ±2.0

Villuendas et al [10,11] determined the behavior of Young's modulus of AA2024 and AA7075 cold deformed before or after aging. This parameter in solubilized, deformed and aged AA 7075 and AA 2024 were slightly lower (<2% reduction) than those of the undeformed specimens. Young's modulus values of solubilized, aged and deformed AA 7075 are also lower (<2% reduction) than those of undeformed specimens, and tend to diminish with deformation degree. In contrast, Young's modulus values of solubilized, aged and deformed AA 2024 are similar to the values for undeformed specimens.

The behavior detected in pure iron is very similar to that detected in pure aluminum and both were different to the behavior determined in aluminum alloys studied in this work. In iron [1] these changes were related to the dislocation density changes. Therefore, when plastic deformation over this material was increased, the dislocation density rose from $3.5\ 10^{-9}$ cm^{-2} at 0% deformation to $14{\cdot}10^{-9}$ cm^{-2} at 6% deformation and, simultaneously, Young's modulus diminished. From this elongation value, a cellular structure of dislocations was formed. Some of these dislocations were pinned with others, and only dislocations inside of the cells ($8{\cdot}10^{-9}$ cm^{-2}) could bow out. Consequently, Young's modulus partially recovered from the deformation value. This behavior is consistent with the Mott model [12] reflected by the following equation:

$$\Delta E / E = -\rho \left[l^2 / 6\alpha \right] \quad (1)$$

where ρ is the dislocation density, l is the average length of dislocations between pinning points, and α is a function of l.

For pure aluminum a similar behavior as iron is assumed. However, in aluminum alloys there is no appreciable changes in the E value. The dislocations density are high [10] but values of parameter l (Mott equation) are very low due to the interaction between nanometric precipitates and dislocations; consequently ΔE/E is very low as really has been experimentally demonstrated.

Young's modulus behavior in nanostructured metallic materials

Several authors have determined the elastic cosntants in nanostructured materials. As examples, Fougere et al [13] determined Young's modulus values by nanoindentation, in nanocrystalline iron obtained by inert-gas condensation and warm consolidation. These authors indicated that porosity was the dominant microstructural effect in determining the diminution of E compared with values obtained in full dense iron. Shen et al [14] determined the elastic moduli in some nanocrystalline metals and alloys prepared by mechanical milling or alloying, using the nanoindentation methodology. For Cu, Ni and Cu-Ni alloys with a grain size between 17 and 26 nm, the E values were similar to those of corresponding polycristals. These authors also indicated that for Fe with a grain size larger than 4 nm, changes in E should be limited (< 10%).

Roca et al [15] measured by ultrasounds the elasticity modulus and Poisson's ratio on nanostructured iron obtained by mechanical milling and on nanostructured copper obtained by severe plastic deformation (ECAP). Results obtained in iron seems indicate that the porosity was not the dominant microstructural effect in the behavior of the elasticity modulus. Changes on Poisson's ratio were not significant. For nanostructured copper and with respect to the shear sound velocities, two different sets of values were detected for each ECAP passes, one fast velocity and another slow velocity. This was detected by tunrning the transversal transductor 90º during the measurement process. Fig. 3 is an image obtained in an osciloscope in which appears the intensity of signal versus time showing the difference between the shear sound velocities (sample of copper with 4 passes). This behavior was related with the texturization of materials during the successive passes into the ECAP process. The texturization disappeared after 5 and after 8 passes in which an only value of shear sound velocity was obtained.

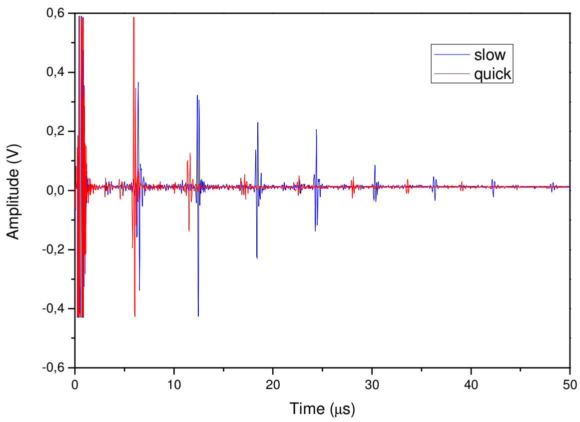

Figure 3. Shear sound velocities on nanostructured copper.

Young's modulus by this technique can only be calculated in isotropic materials as the original material and those obtained after 5 and 8 passes. Values of E obtained were 132 GPa (0 passes), 133 GPa (5 passes) and 118 GPa (8 passes). Note that Young's modulus for 5 passes is almost the same as the original material but a decrease of this parameter was detected for 8 passes (~ 10% reduction of Young's modulus). Results obtained by ultrasonic measurements give valuable information about structural changes in materials subjected to severe plastic deformation. This technique can be complementary with other microstructural techniques.

Llorca-Isern et al [16] have prepared a nanostructured magnetic Cu-Co-Fe alloy (50Cu-25Co-25Fe) by mechanical alloying. After this, the determination of E by the ultrasonic method was attempted but it was not succesfully. Fig. 4 shows an image of osciloscope in which appears the intensity of signal versus time for the corresponding alloys. A high signal attenuation was achieved and it was not due to the intrinsec magnetic properties of this material, because this attenuation effect not occurs in another magnetic materials, as for example iron prepared in a similar form [15].

Young's modulus behavior in metallic alloys in loading-unloading processes

Morestin et al [6] determined the diminution of Young's modulus with plastic deformation (tension and compresion tests) using a loading/unloading system, for different steels used in metal stamping processes. They detected a decrease of 15% or higher, immediately after unloading and a partial recovery of E with time reaching a constant value. In all the cases these values were lower than the original ones. These authors indicated that in the 90's almost all the elastoplastic software applied in metal forming processes not take into account these changes; consequently, results predicted were different of the experimental results obtained. This behavior is considered today as is shown in the revised literature [2,3]. As an additional example, Liu et al [17] indicated that Young's modulus is a crucial material property parameter affecting springback simulation. They studied the variation of E with plastic deformation for a tube made of 3A21 aluminum alloy through a repeated loading-unloading experiment, obtaining a linear function to describe the relationship between E and plastic strain. The comparison made between simulation and experimental data showed that the accuracy of springback prediction improved significantly by 18% when the variation of Young's modulus was considered.

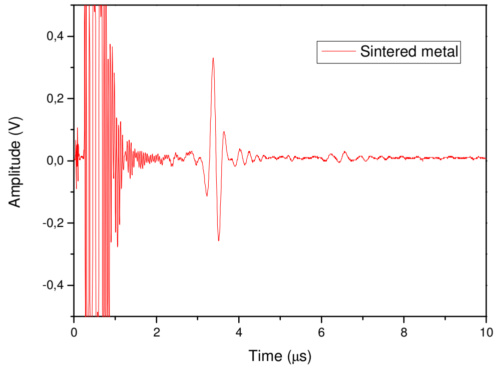

Figure 4. Shear sound velocities on nanostructured Cu-Co-Fe alloy.

Our research team has developed some loading-unloading experiments on UNS G 10180 and UNS G10430 carbon steels (with 0.18 and 0.43% C, respectively). An extensometer with a l_0 = 50 mm was used for the strain measurements. After measuring E at the initial stage during loading, ($\varepsilon = \varepsilon_0 = 0$), the sample was deformed to a selected strain ($\varepsilon = \varepsilon_1$) and unloaded; E was measured during unloading and the value of this parameter was calculated considering the new cross section. The sample was left unloaded during 48 hours. This process was repeated for greater strains (ε_2, ε_3, ε_4…). In each case Young's modulus of materials during loading and unloading were determined. Results obtained are included in Table 2.

Considering the E values during loading, this parameter for both materials diminishes in a similar form that has been described in Fig. 2. Additionally a clear difference between Young's modulus values measured during loading and unloading are observed; values of this parameter during unloading are lower than those measured during loading. These differences varied between 18 and 40 GPa (UNS G10180) and between 20 and 49 GPa (UNS G10430). These results also indicate that E partially recovers between unloading and the next cycle of loading. The results obtained are similar to those obtained by Morestin et al [6] in steels with 0.14 and 0.38%C.

Table 2. Young's modulus values of carbon steels after loading-unloading in tension test.

Step	Plastic Strain %	*	E (GPa)	Step	Plastic Deformation	*	E (GPa)
1	0-0.90	L U	206 172	1	0-1.0	L U	204 167
2	0.90-2.2	L U	210 170	2	1.0-2.3	L U	208 159
3	2.2-3.2	L U	200 165	3	2.3-3.0	L U	202 161
4	3.2-4.3	L U	208 171	4	3.0-3.9	L U	206 164
5	4.3-5.6	L U	202 179	5	3.9-5.2	L U	193 165
6	5.6-8.0	L U	204 183	6	5.2-6.9	L U	183 160
7	8.0-9.5	L U	197 178	7	6.9-7.8	L U	195 163
8				8	7.8-9.0	L U	180 160

*Note: L, measurement during loading; U measurement during unloading.

Summary

Young's modulus of metallic alloys change, in most cases, with plastic deformation achieving levels of reduction of 10-15% with respect to the annealed materials; during the springback of some materials this diminution can be higher. In each case, a complete study about changes of this parameter with plastic deformation is necessary to obtain a better understanding in the inelastic effects and improve the accuracy in the prediction of springback for metallic materials.

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