ISSN 1516-392X

INVESTIGATION OF INFLUENCE OF BAUSCHINGER EFFECT ON THE MECHANICAL PROPERTIES OF AN AISI 1045 STEEL[1]

Juliana Dagnese[2]
Alexandre da Silva Rocha[3]
Thomas K. Hirsch[4]

Abstract

Specimens of AISI 1045 steel of different batches were first loaded in uniaxial homogeneous tension tests until a certain amount of plastic strain and then reloaded in reverse direction. The tensile and compression tests were carried out in a Gleeble® 3500 thermo-mechanical testing machine. The determination of some characteristic values makes it possible to describe the Bauschinger effect quantitatively for three different temperatures. The mechanical properties and microstructure were also characterized by standard tension tests and image analysis software for different materials batches. It was possible to see the influence of the investigated temperature range on the Bauschinger effect. The results reveal that the Bauschinger effect can be significant for several forming operations.
Keywords: Kinematic hardening; Bauschinger effect; AISI 1045 steel; Predeformation.

INVESTIGAÇÃO DA INFLUÊNCIA DO EFEITO BAUSCHINGER NAS PROPRIEDADES MECÂNICAS DO AÇO AISI 1045

Resumo

Amostras provenientes de diferentes lotes de aço AISI 1045 foram primeiramente deformadas em ensaio de tração uniaxial até atingirem um determinado grau de deformação plástica. Após o descarregamento, as amostras foram plasticamente deformadas na direção inversa. Os testes de tração e compressão foram realizados numa máquina de testes termomecânicos Gleeble® 3500 em três diferentes condições de temperatura. O cálculo de algums valores característicos torna possível descrever o efeito Bauschinger. As propriedades mecânicas e microestruturais dos materiais dos diferentes lotes também foram caracterizadas por meio de testes de tração e software de análise de imagens. Assim, foi possível investigar a influência da faixa de temperatura abordada na magnitude do efeito Bauschinger.
Palavras-chave: Endurecimento cinemático; Efeito Bauschinger; Aço AISI 1045; Pré-deformação.

[1] *Contribuição técnica ao 66º Congresso Anual da ABM, 18 a 22 de julho de 2011, São Paulo, SP, Brasil.*
[2] *Master Degree Student at Universidade Federal do Rio Grande do Sul, Porto Alegre*
[3] *Prof. Dr. at Universidade Federal do Rio Grande do Sul, Porto Alegre*
[4] *Privat Doscent at Stiftung Institut für Werkstofftechnik, Bremen, Germany*

1 INTRODUCTION

One of the chief characteristics of the plastic deformation of metals is the fact that the shear stress required to produce slip continuously increases with increasing shear strain. The increase in the stress required to cause slip because of previous plastic deformation is known as strain hardening, or work hardening. In most materials, hardening in one direction will affect subsequent plastic response in other directions. This relationship is called kinematic hardening. If a specimen is deformed plastically beyond the yield stress in one direction, e.g., in tension, and then after unloading to zero stress it is reloaded in the opposite direction, e.g., in compression, it is found that the yield stress on reloading is less than the original yield stress**.** This dependence of the yield stress on loading path and direction is called the Bauschinger effect.[1]
In general, there are two main schools to explain the Bauschinger effect: namely, internal stress and dislocation theories. The earlier theories relied on internal stress effects and especially on macroscopic residual stresses developed as a result of inhomogeneous deformation of the grains of a polycrystalline metal.[2,3] These ideas were supported by the work of several authors, such as Heyn (1914 *apud SIMSIR et al., 2010, p. 4480)*[3], Masing (1926 *apud SIMSIR, 2010, p. 4480*),[3] Schmid and Boas (1950 *apud ABEL and MUIR, 1972, p. 490*),[2] and Thompson and Wadsworth (1958 *apud ABEL and MUIR, 1972, p. 490*).[2] Abel and Muir[2] report: “The need for a different approach became apparent when Gough, Wrights and Hanson (1924) and Sachs and Shoji (1927) demonstrated the existence of a Bauschinger effect in brass single crystals.” Recently some theories based on the dislocation theory have been approached by some authors.[2,3] According Orowan (1959 *apud ABEL and MUIR, 1972, p. 490),*[2] the two main approaches rely on “back-stress” effects associated with dislocation pile-ups, or on the development during prestraining of directionality in the driving force for dislocation motion.
It was already observed by Dieter[1] that the phenomenon of strain hardening is difficult to accommodate within the theory of plasticity without introducing considerable mathematical complexity. Because of this difficulty, the Bauschinger effect is commonly ignored in plasticity theory, and it is usual to assume that the yield stress in tension and compression are the same, even after a prestress.
In this work the Bauschinger effect was quantitatively investigated by means of conventional parameters for bars of hot-rolled AISI 1045 steel obtained from a combined drawing-straightening process. Tension-compression experiments were carried out using a Gleeble(R) 3500 thermo-mechanical testing machine, which combines the properties of a hydraulic testing machine with those of a quenching dilatometer, and then it was also possible to evaluate the effect of a temperature range up to 120°C on the Bauschinger effect. The microstructure and chemical composition were characterized by image analysis software and optical emission spectroscopy, respectively, for the different materials batches.

2 EXPERIMENTAL PROCEDURE

2.1 Material

The material used for the experiments, bars of AISI 1045 steel, was obtained from a combined drawing-straightening process. In this manufacturing route, bars of as hot-rolled material are first horizontally and vertically pre-straightened by a series of rolls, after that they are shot blasted and drawn, finally they are cut, polished and straightened by crossed rolls. Figure 1 shows the process sequence.[4]

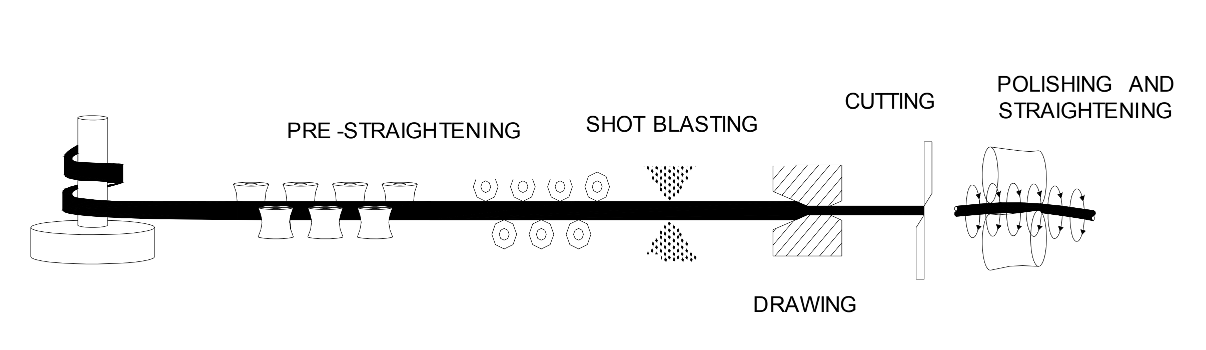

Figure 1. Proceesing steps in the straightening and drawing of steel bars.[4]

The bars have a final diameter of 22 cm and two different batches with differences in the chemical composition were investigated by means of optical emission spectroscopy. The chemical compositions are presented in Table 1.

Table 1. Chemical composition

Batch	C	Si	Mn	P	Cr	Ni	Mo	Cu
A	0,434	0,237	0,789	0,024	0,126	0,0762	0,0289	0,093
B	0,443	0,232	0,662	0,027	0,086	0,0546	0,0147	0,078

The microstructure (Figure 2) consists of ferrite and perlite, typical for medium carbon steels. The images are representative from the axial section of the bars.

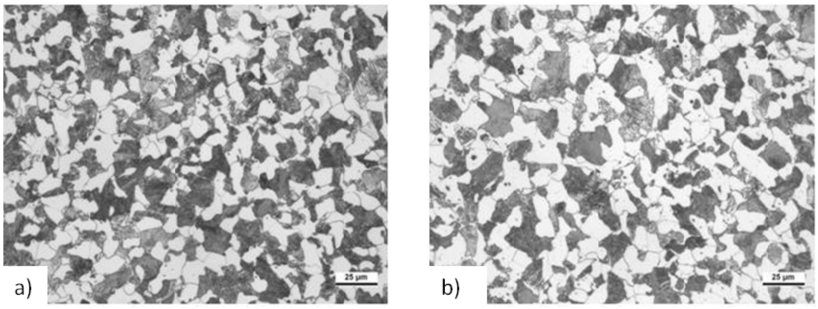

Figure 2. Axial section microstructure of the bars. (a) Batch A; b) Batch B.

The quantitative analyses made by means of the Software QWinPro V3.2.1 gives really small grain sizes for this material which is totally according to an industrial production.
The grain size analized according to DIN EN ISO 643[5] (or ASTM E 1382[6]) is in the mean around 11, which is a very good small grain size of this type of material.
The mechanical properties of the material were evaluated by means of uniaxial tensile tests carried out using an Instron 5985 tensile testing machine. Mechanical tests were performed according to standard test method ASTM E8M[7] to determine the ultimate tensile strength, 0.2% proof stress and elongation, and ASTM E111[8] to determine the initial elastic modulus. The gauge lengths of the tensile test sample was 5 mm and the diameter 20 mm. The velocity during the tension test was $1x10^{-4}$ 1/second. The mechanical properties were summarized in Table 2.

Table 2. Mechanical properties by tension tests

Batch	Yield	Tensile Strength	Young´s Module	Elongation

	(MPa)	(UTS) (MPa)	(GPa)	(%)
A	387,5	688	216,5	12,9
B	372	653	200,5	12,3

2.2 Experimental Set-Up and Testing

The experiments were carried out using a Gleeble® 3500 thermomechanical testing machine, which combines the properties of a hydraulic testing machine with those of quenching dilatometer. The specimens used in the tests were manufactures according to Figure 4. To improve the measurement technique, the machine was upgraded with a laser extensometer, which allows simultaneous measurement of both the longitudinal and transverse strains.

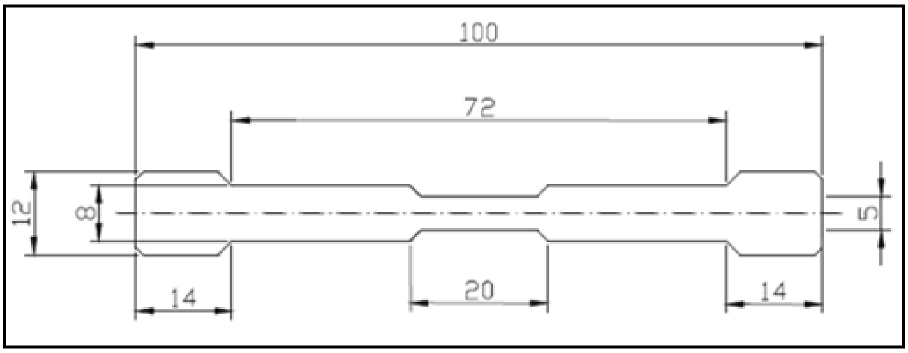

Figure 3. Specimens for tension-compression tests in Gleeble® 3500 thermomechanical testing machine.

The longitudinal strain was measured on two opposite sides of the specimen. To measure the longitudinal strain, gauge marks were welded on the specimen in a distance of 10 mm gauge length on both sides in the middle of the specimen. Measurements were performed by two laser beams using shadowing effects. The transversal strain in the centre of the specimen was measured by the same method. To apply any sample temperature the specimen was heated by conduction. The temperature is measured by a thermocouple in the middle of the gauge length. Firstly, the specimens were mounted in the thermo-mechanical testing machine and the test chamber was depressurized. The test chamber was kept under vacuum during the whole test. Subsequently, the specimens were heated to each preset temperature. A strain rate controlled tension-compression test at a constant strain rate of 1x10-4 s-1 was performed after the stabilization of temperature. After the completion of the test, the specimens were cooled to room temperature by resetting the vacuum to ambient pressure. Temperature (T), stress (σ), longitudinal (ε_l) and transverse (ε_r) strains were recorded during the tests.
Five specimens were used for the experiments and the table 3 shows the conditions for each test.

Table 3. Experimental conditions for the specimens

Specimen	Material batch	Temperature (° C)
1	A	25
2	B	25
3	A	80
4	B	80
5	B	120

2.3 Bauschinger Effect Parameters

ISSN 1516-392X

The quantification of the Bauschinger effect is a difficult for the ones that try to understand and explain the phenomena.[2,3,9,10] The literature suggests different parameters, but the results interpretation and comparison is a scientific challenge up to now.

The major problem with the parameters suggested to date is that each individual parameter can usually characterize only one or a few aspects of the Bauschinger effect. Moreover, the aspects associated with each parameter cannot simply be superposed on the aspects associated with other parameters due to the complicated interactions between mechanisms.[3]

Some authors[2,9] concluded that the magnitude of the Bauschinger effect could not be assessed in terms of one parameter, such as the lowering of the yield or flow stress on reverse loading, alone.

For the Bauschinger parameters calculation, a diagram which shows the absolute stress value vs. the cumulative strain reconstructed from the conventional stress-strain diagram obtained from the experiments described in section 2.2, were used. (Figure 4).

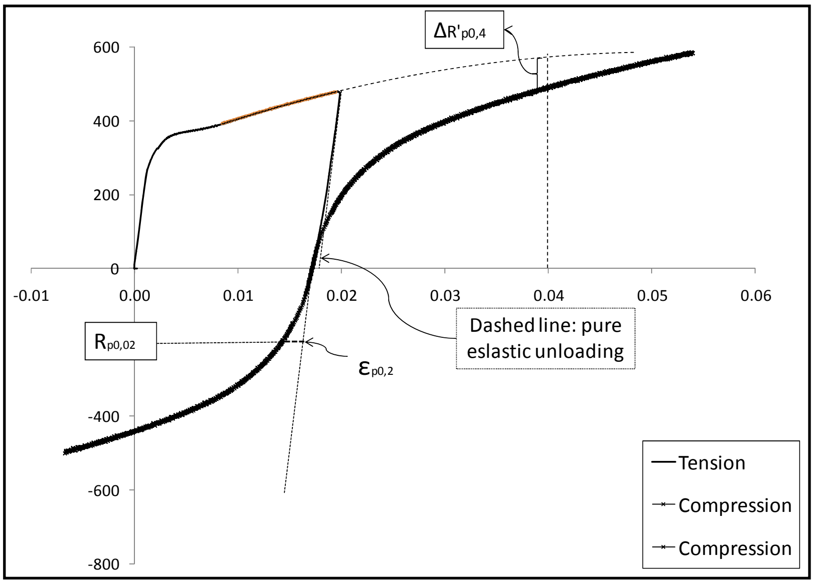

Figure 4. Reconstructed stress (σ) vs. cumulative strain (ε) diagram and the graphical illustration of parameters used in quantification of the Bauschinger effect. The dashed lines represent hypothetical extensions of forward and backward flow curves if the strain path was not reversed.

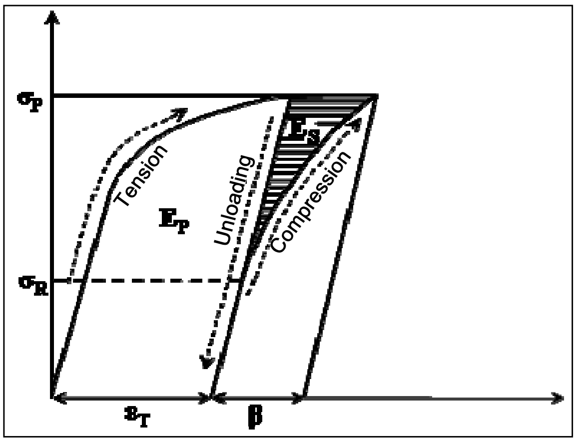

Figure 5. Bauschinger parameters ilustration.

Abel e Muir[2] describe the Bauschinger strain as total reverse strain that occurs during unloading and reverse loading at a stress level defined by $\sigma = -\sigma p$ where σ is

ISSN 1516-392X

the prestress (maximum stress for tension). The parameter β_ε *(Bauschinger strain parameter)* is β and the plastic prestrain ε_p ratio and it usually associated with the transient softening effect.(3)

$$\beta_\varepsilon = \frac{\beta}{\varepsilon_p} \quad (1)$$

The magnitude of this parameter represents a quantification of the Bauschinger effect. In the case of $\beta_\epsilon = 1.0$, the pre-strain was fully reversed and there is no hardening ($\beta_\epsilon < 1.0$) and nor softening ($\beta_\epsilon > 1.0$).
Scholtes(5) assumes the parameter $\Delta R'_{p\varepsilon}$, which corresponds to:

$$\Delta R'_{p\varepsilon} = \sigma \quad \sigma_R \quad (2)$$

Where σ is the maximum stress for the tension loading and σ_R is the maximum stress for compression, at a certain amount of plastic strain. In this case, the stress-strain curve must to be extrapolated, according to Figure 5.

3 EXPERIMENTAL PROCEDURE

3.1 Tension-Compression Tests

This material shows a pronounced Bauschinger effect, that means differences of stress-strain curve in forward deformation. If you apply some change of the loading direction, then the material shows a pronounced Bauschinger effect, which means in the changing of the loading direction to compression there is almost no pronounced yield straight compared to the tensile test data. As can be observed in Figure 6 differences also occur after deformation at Room Temperature and deformation at 80°C and at 120°C respectively. Local variations of stresses for the stress-strain curve at 120°C are due to dynamic strain hardening- a transient restriction of dislocation movement.

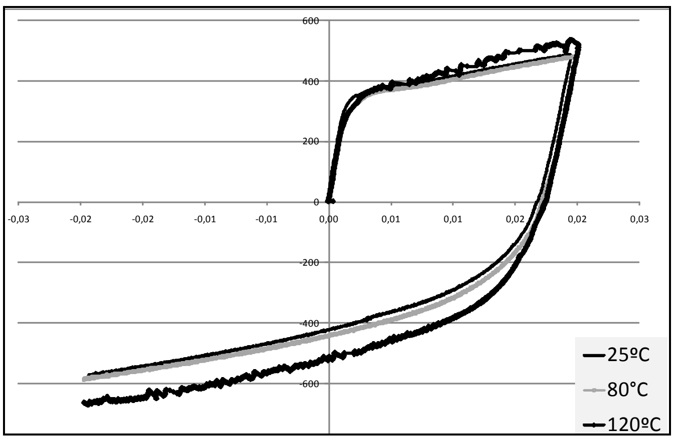

Figura 6. Tension – compression tests for three different temperatures (25°C, 80°C and 120 ºC).

Considering the drawing process, it seems to be interesting to consider this data, for example, for the pre-straightening and the shot-blasting, which are a deformation in one direction and probably the drawing processes itself could be a deformation in the opposite direction, so Bauschinger effect probably will occur. Furthermore, the tension tests have demonstrated that the true stress true strain curves for A has the highest true stress at certain given true strain and it is also possible to notice that the

ISSN 1516-392X

Lüders band is not present for this batch. Whereas the batch B shows lower true stresses at a certain given strain and the Lüders band appears. It suggests that the material of the batch A already had some hardening before any deformation step in the drawing process. It represents that the material can present different states of deformation prior the drawing processes. All these results demonstrate that material behavior will show differences depending on the detailed previous mechanical history of the material.

3.2 Bauschinger Effect Parameters

Bauschinger test data was evaluated in a conventional way according to section 2.3. The data is summarized on Table 4.
The maximum stress σ_{max} in the first tensile direction is indicated in the tables. There is no big difference between the speciments tested at room temperature and at 80°C, Otherwise, the σ_{max} is higher for 120°C.
If ε_p is set to 0,2% the indices are set to this value , then it is possible to observ that the bauschinger strain parameter β_ε decreases with the increasing of the temperature. It means the bauschinger effect is lower for 120°C. The $\Delta R'_{p0,4}$ also decreases significantly with increasing temperature.
Parameter $R_{p0,02}$, which one can be seen on Figure 5, is significantly higher for 120°C. That means the strain deviation ε_p of 0,2% occurs at a higher stress. It is clear the Bauschinger effect seems to be lower.

Tabela 4. Bauschinger effect parameters.

Sample	T=25°C		T = 80°C		T = 120°C
	1	2	3	4	5
Youngs Modulus [MPa]	201295	238039	230993	227360	229763
$Rp_{0,2}$ [MPa]	183	181	180	199	248
σmax [MPa]	478	487	478	481	534
$\beta_\delta=\beta/\varepsilon_p$	1,37	1,42	1,35	1,27	1,08
$\Delta R'_{p0,4}$ [MPa]	107	105	99	78	76

4 CONCLUSION

The results demonstrate that this material shows a pronounced Bauschinger effect and demonstrate that material behavior will show differences depending on the detailed previous mechanical history of the material. This fact confirms that the pre-strain levels are quite and must be considered in Bauschinger effect analysis.
The calculation of the parameters made it possible to quantify the Bauschinger effect and results showed that the Bauschinger effect decreases with increasing temperature in the range of temperature evaluated.
Furthermore, there is one thing that should be noted. There are many factors that could affect the Bauschinger effect magnitude, such as chemical composition, grain size, distribution of precipitated particles, hardness, strain rate, etc. All these characteristics must be well known before the correct understanding of the Bauschinger effect and its quantification.

Acknowledgement

The authors thank the support of Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES, Universidade Federal do Rio Grande do Sul, Gerdau in Brazil and Stiftung Institut für Werkstofftechnik - IWT Bremen, in Germany.

REFERENCES

1 DIETER, G. E. Mechanical Metallurgy, 2nd ed. New York: McGraw-Hill, 1976.
2 ABEL, A., MUIR, H. The Bauschinger Effect and Discontinuous Yielding. Philosophical Magazine, v. 26, n. 2, p. 489 — 504, 1972.
3 SIMSIR, C., DALGIÇ, T., LÜBBEN, T., IRRETIER, A., WOLFF, M., ZOCH, H. W. The Bauschinger Effect in the supercooled austenite of SAE 52100 steel. Acta Materialia, v. 58, p. 4478 -4491.2010.
4 NUNES, R. M., METZ, M., HIRSCH, T. K., ROCHA, A.S. Análise de Tensões Residuais em Barras de Aço AISI 1048 Produzidas por Trefilação Combinada. in: 63 congresso anual da ABM, 2008, Santos. Congresso Anual da Associação Brasileira de Metalurgia e Materiais, 2008. v. 1. p. 341-350.
5 DIN EN ISO 643. Steel Micrographic Determination of the apparent grain size. European Standard. Deutsches Institut für Normung e. V. 2003
6 ASTM E 1382 – 97. Standard Test Methods for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis. ASTM International. 2004
7 ASTM E8M – 04. Standard Test Methods for Tension Testing of Metallic Materials. ASTM International. 2009
8 ASTM E111 – 04. Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus. ASTM International. 2004
9 SCHOLTES, B. VÖHRINGER, O., MACHERAUCH, E. Die Auswirkungen des Bauschingereffekts auf das Verformungsverhalten von normalgeglühtem Stahl Ck 45. Steel Research, v. 56, n. 3, p. 157 - 162. 1985.
10 ABEL, A., MUIR, The Bauschinger Effect and Stacking Fault Energy. Philosophical Magazine, v. 27, n. 3, p. 585 — 594, 1973.