ROZPRAWY INŻYNIERSKIE • ENGINEERING TRANSACTIONS • 31, 3, 417—428, 1983
Polska Akademia Nauk • Instytut Podstawowych Problemów Techniki

THE BAUSCHINGER EFFECT IN STRUCTURAL ALUMINUM ALLOYS

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The paper presents test results for the Bauschinger effect on various structural aluminum alloys (PA7N, PA4N, PA2N). The experiments were carried out for the raw material, obtained directly from the factory. The range of initial overstrain ε_w was 0.2 — 9%. The results of the tests were computed according to two of the most common approaches regarding the defining of the Bauschinger effect. Large differences between both approaches were observed. The experiments proved that the Bauschinger effect for a structural metal may have a diverse character. Essential differences may not only occur in various kinds of material but also within the same alloy.

1. Introduction

The Bauschinger effect is of considerable practical importance since it may readily occur in the use of cold-formed or plastically prestressed structural components. However, to date, only limited data have been available concerning the Bauschinger effect especially in high-strength alloy steels and aluminum alloys. Moreover, when studying this problem it can be noticed that different investigators evaluated the Bauschinger effect in several ways. This is why a comparison of their results is often very difficult and leads to different conclusions. This was also observed by Miastkowski [1] and Moskwitin [2]. A detailed review of the work concerning the Bauschinger effect in an unaxial loading can be found in the author's work [3].

Two of the most common approaches in defining the magnitude of the Bauschinger effect are explained in Fig. 1. If $R'_{\varepsilon_{pl}}$ is the initial yield stress (based on ε_{pl} % offsets) and $R''_{\varepsilon_{pl}}$ the yield stress in the reversed direction of loading, then the magnitude of the Bauschinger effect can be evaluated by the Bauschinger effect factor (BEF) as is given in the formula (1.1)

$$\text{BEF}=\frac{R'_{\varepsilon_{pl}}}{R''_{\varepsilon_{pl}}}. \tag{1.1}$$

By this definition, the BEF for a specimen initially overstrained in tension would be the ratio of the compressive yield stress upon reverse loading to the initial yield stress in compression. Of course, in this case we assume that the yield strength in tension and compression are equal. In such a way the Bauschinger effect was determined by its discoverer J. Bauschinger [4, 5] and later by other investigators as

MASING [6], SACHS and SHOJI [7], WELTER [8], HOGE *at al.* [9]. But in some other works for example [10, 11, 12, 13, 14] we can find the definition of the BEF given by the formula (1.2) as the ratio of the yield stress upon reversed loading to the stress at the overstrained point.

$$\text{BEF} = \frac{R''_{\varepsilon_{p1}}}{R'} . \tag{1.2}$$

In this approach strain-hardening is taken into account by accepting as the initial yield stress the maximum stress R'. This fact, in the author's opinion, is open to discussion. These values can be close to each other but this depends much on the value of the permanent strain ε_{p1} used in obtaining the yield strength. Moreover, with such an assumption age-hardening is not taken into account, either.

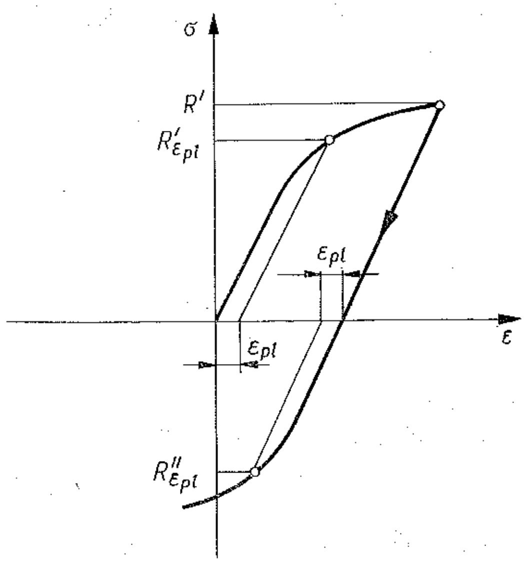

FIG. 1.

Therefore, BEF base on the formula (1.1) evaluates the differences between the mechanical characteristics for a virgin material and a material which has been overstrained. BEF based on the formula (1.2) evaluates actual anisotropy of the material which has been overstrained, in other words, the differences between strain resistance of overstrained material upon reverse loading and upon loading in the same direction. Such various ways of defining the magnitude of the Bauschinger effect of course must lead to different conclusions. Moreover, most of the investigators evaluate the Bauschinger effect using only one approach. Only MILLIGEN, KOO and DAVIDSON [15] describe the test results carried out on high-strength steel using both approaches. But their results for materials having martensitic, pearlitic and bainitic structures show only small differences in the BEF as computed by the two approaches.

The main object of this paper is to evaluate the magnitude of the Bauschinger effect in structural aluminum alloys and show the differences between the BEF as computed by the two approaches.

2. Experimental procedure

The experiments were carried out on three different kinds of aluminum alloys using a tension-compression test. Some basic mechanical properties specified by the producer and the chemical composition of those materials are shown in Table 1. As opposed to the majority of similar works, investigations were carried out for a large range of initial overstrain (from 0.2% to 9%) and concerned structural alloys obtained directly from the factory, without any heat-treatment aiming at increasing the homogeneity and isotropy of the material. This had often been applied by other investigators [10, 11, 12, 13, 16].

Table 1.

Material	Main alloying elements (in percent) except aluminum	Mechanical properties (quaranteed minimum values)
PA7N(ta) (AlCu4Mg1)	Cu 3.8–4.8 Mg 1.2–1.8 Mn 0.4–1.1	$R_r=410$ MPa $R_{02}=250$ MPa $a_{10}=9\%$
PA4N(tb) (AlMg1Si1)	Mg 0.7–1.5 Mn 0 2–1.0 Si 0.7–1.5	$R_r=270$ MPa $R_{02}=200$ Pa $a_{10}=10\%$
PA2N(z4) (AlMg2)	Mg 1.8–2.8 Mn 0.2–0.6	$R_r=180$ MPa $a_{10}=5\%$

All tests were carried out on circular tubes having an external diameter of 20 mm and thickness of the wall 2 mm. For each alloy the specimens were cut out from five randomly chosen 4 m long bars. Each series consisted of 5 specimens 300 mm long. The specimens of each series were separately initially overstrained in tension to the assumed values $\varepsilon_w=0$; 0.2; 0.5; 1; 2; ... 9%. Only in the case of aluminum PA2N the maximum percent of tensile overstrain that could be obtained without failure was 4%. The strain was measured during overstraining by an extensometer and also after loading. The permanent strain distribution alongside the specimen was obtained by measuring local elongations between scribing every one centimeter line. Compressive tests were carried out on the tube specimens 100 mm high cut from overstraining specimens. Such lengths of the specimen allowed to obtain homogeneous stress in its middle part and also avoid buckling in the range of applied loads.

The experiments were planned to determine the influence of initial overstrain in tension on the stress- strain relations in compression. The change of the modulus of elasticity and field strength at: 0.02; 0.05; 0.1; 0.2% offsets were examined. Stattistical analysis of all test results was done, assuming normal distribution of material properties and using the t-student test. All calculations were done numerically using a specially prepared programme, which made the full elaboration of results of the compressive or tensile test possible.

3. Results and discussion

The investigations carried out enable to observe that all alloys used for experiments were very homogeneous. Some results of tensile and compressive tests for virgin material are shown in Table 2. It can be seen that deviations of the results were rather very small. Also the deviations of the results for overstrained materials were much the same and usually the variation coefficients $(\nu\,(R_{\varepsilon_{pl}}))$ of yield points at: 0.02; 0.05; 0.1; 0.2% offsets fluctuated in the range 1–4%. Analysis of the results of measuring local elongations indicates that the permanent strain distributions alongside the specimens were usually rather regular ans close to the assumed values of overstrain. This also means that the material was homogeneous. According to Marciniak [17], distribution of the permanent strain alongside the bar depends very much on homogeneity of the material and geometric imperfections. Even the smallest structure or geometric imperfections which are absolutely negligible for mechanical properties as the yield point, modulus of elasticity etc. cause essential change in the distribution of permanent strains. Figure 2 shows the Bauschinger effect factor (BEF) for different offsets versus percent tensile overstrain for the aluminum alloy PA7N. If BEF is defined by the formula (1.1), the graph (Fig. 2a) shows that for a tested material the largest Bauschinger effect appears for initial prestrain up to 0.5%. The magnitude of BEF depends on the value of the permanent strain (ε_{pl}) used in obtaining the yield strength. The Bauschinger effect increases with a decrease of the value of permanent strain ε_{pl}. For example, initial tensile overstrain up to 0.5% makes the compressive yield strength at 0.2 percent offset decrease about 8% (BEF=0.92) and the yield strength at 0.02% offset about 25% (BEF=0.75) Figure 2a also shows that with a further increase of tension overstrain the compressive yield strength starts to increase and starting from some values of overstrain it can be even higher than for a virgin material (BEF becomes greater than unity). This means that strain-hardening appears also in loading in the reverse direction to the initial overstrain and according to the formula (1.1) the Bauschinger effect disappears. It can be noted that with a decrease of the value of ε_{pl} used in obtaining the yield strength, the Bauschinger effect disappears for larger values of tensile overstrain.

In the case when BEF is defined by the formula (1.2), the graph (Fig. 2b) shows that BEF initially decreases with increasing values of tensile prestrain up to approximately 2 percent at which point it becomes effectively constant and depends only on the value of the permanent strain used in obtaining the yield strength. For example, it tends to stabilize at a value of about 0.81 for yield strength at 0.2% offset and at a value of 0.6 for yield strength at 0.02% offset.

Table 2.

Material	Kind of test	Modulus of elasticity (MPa)	Yield stress and variation coefficient							
			$R_{0.02}$ (MPa)	$\nu(R_{0.02})$ (%)	$R_{0.05}$ (MPa)	$\nu(R_{0.05})$ (%)	$R_{0.1}$ (MPa)	$\nu(R_{0.1})$ (%)	$R_{0.2}$ (MPa)	$\nu(R_{0.2})$ (%)
PA7N(ta)	tensile	75729	295.2	0.6	307.7	0.6	318.0	0.6	328.6	0.5
	compres-sive	73974	292.6	3.6	308.7	1.3	321.7	0.9	336.1	0,8
PA4N(tb)	tensile	71623	210.2	4.6	218.0	3.9	223.8	3.5	230.1	3.4
	compres-sive	71250	200.1	2.7	212.8	2.5	223.8	3.2	232.3	2.7
PA2N(z4)	tensile	67229	172.0	4.2	187.2	1.6	193.2	0.6	201.8	1.4
	compres-sive	66708	143.2	9.1	167.8	3.4	183.1	1.5	196.4	0.9

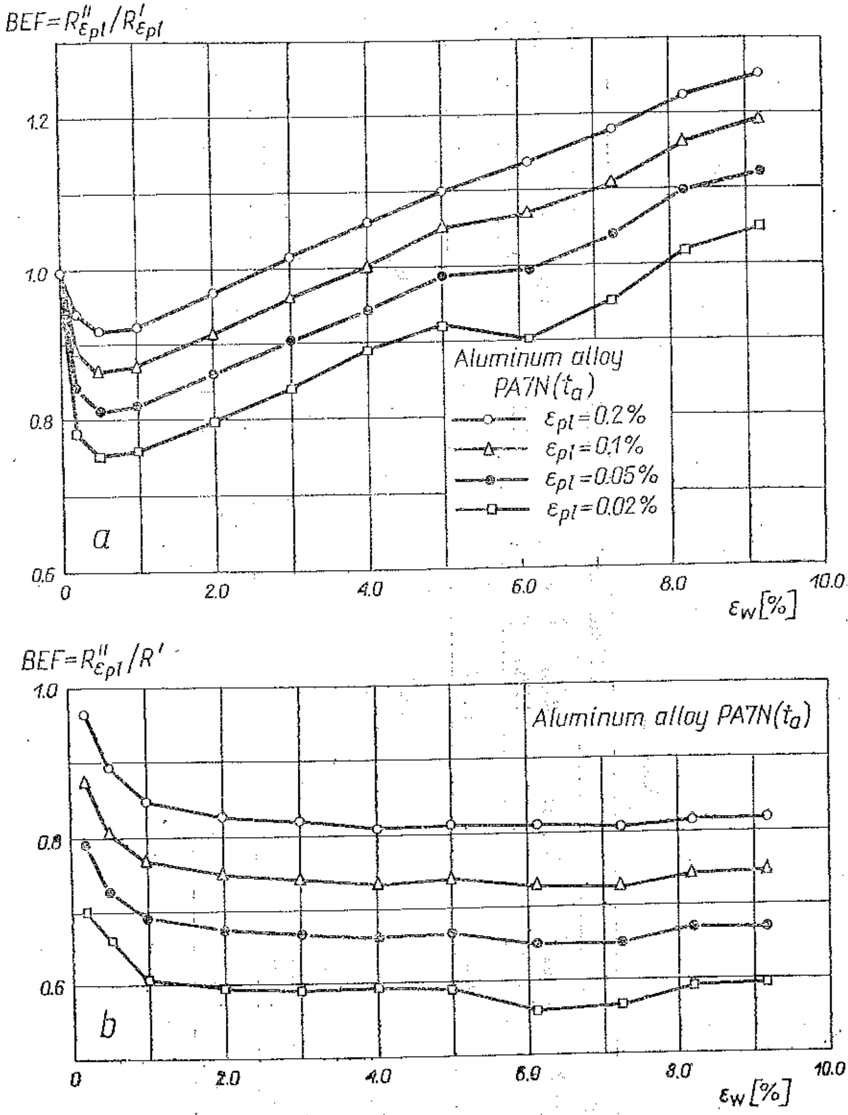

FIG. 2.

Figure 3 shows average compressive stress-strain curves for all series of PA7N alloys overstrained in tension up to different values. For small values of tensile overstrain (ε_w=0.2–1.2%) the whole curves are below the curve for a material not overstrained. The differences between the shape of the knee of the curves can also be noted. For a material initially overstrained up to higher values, increasing strain-hardening is observed.

Very much the same results were obtained for aluminum alloy PA4N. Figure 4 shows the relationship between BEF computed according to both formulas and the value of tensile overstrain. For both cases not only the character of diagrams but

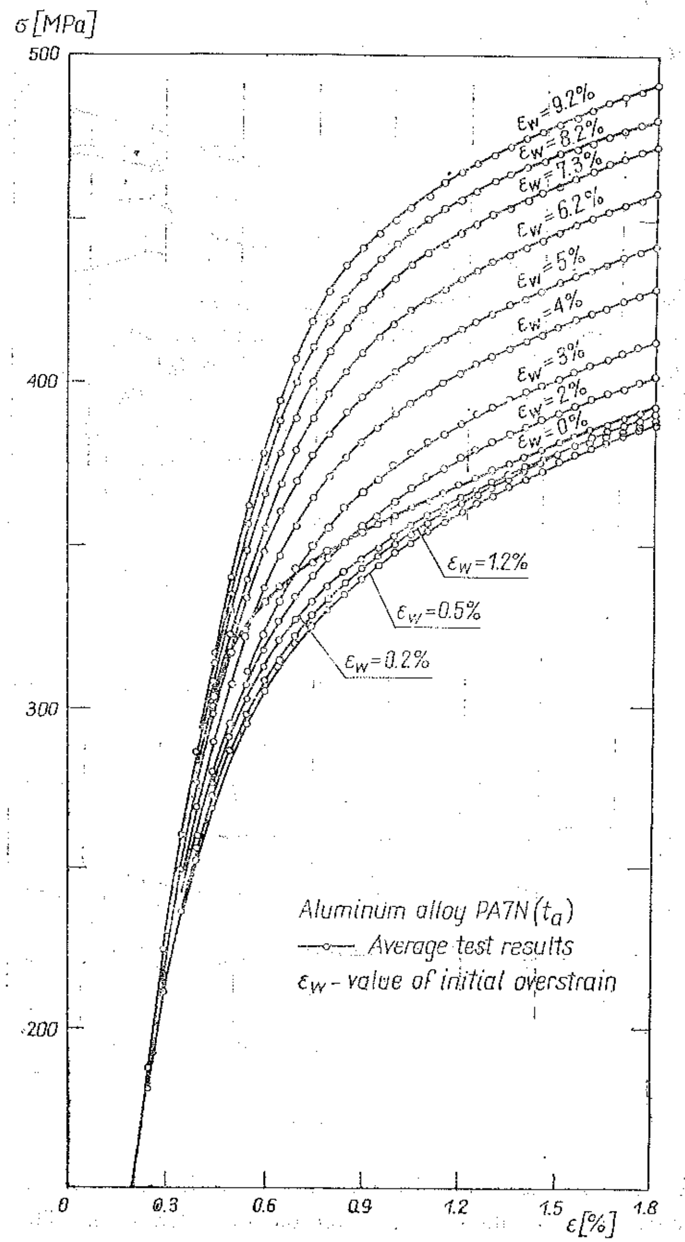

FIG. 3.

also the values of BEF are as it was described earlier for PA7N alloy. The obtained results are also in good agreement with the test results of other investigators carried out for such materials as copper [16], brass and pure aluminum [7].

The results for PA2N alloy were essentially different than for the two alloys described above. Figure 5 shows average compressive stress-strain curves for all tested series of alloy PA2N. It can be observed that all curves for a material initially

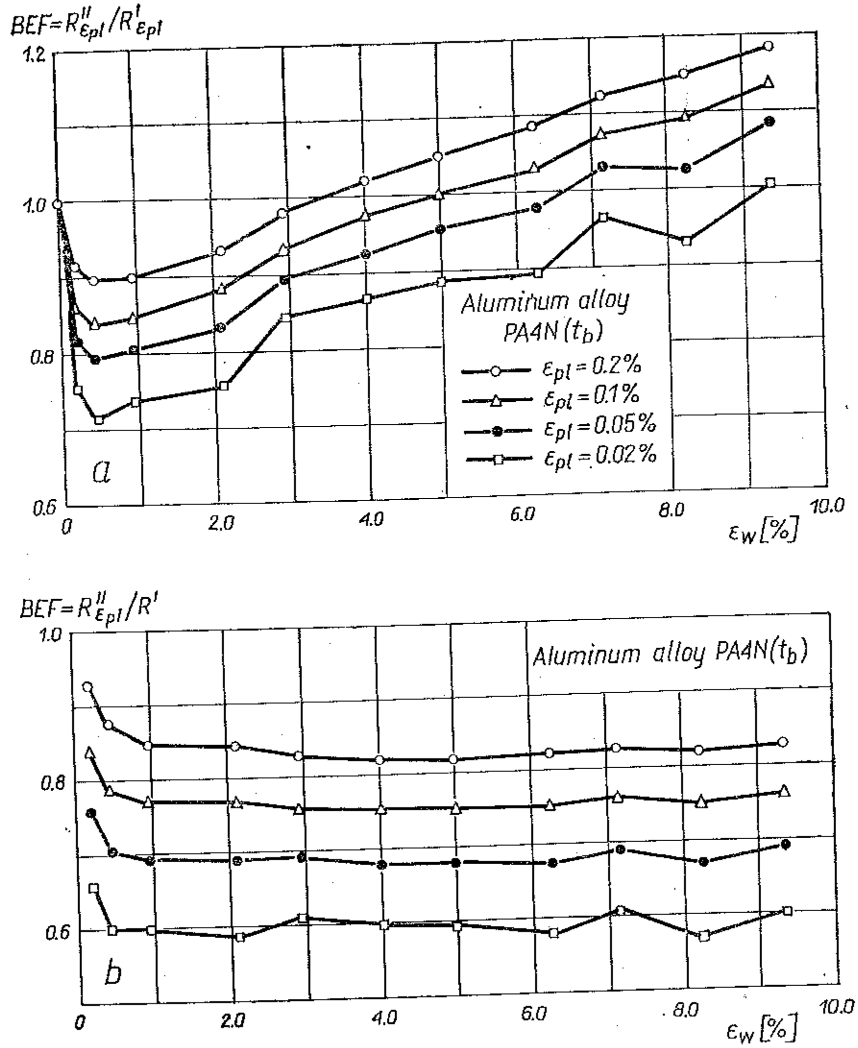

FIG. 4.

overstrained are above the curve for a virgin material. Figure 6a shows that yield strength increased with increasing amounts of overstrain. The increase of yield strength is the greater the smaller is the value of ε_{pl}. For example, for initial overstrain $\varepsilon_w = 4\%$ the yield strength based on 0.2% offset increases about 12% (BEF=1.12) and the yield strength based on 0.02% offset increases about 23% (BEF=1.23). So, according to the formula (1.1) starting from the smallest value of initial overstrain, the Bauschinger effect does not exist: the value of BEF is higher than unity. Such a difference is not shown by the relationship between BEF computed by the formula (1.2) and the values of tensile overstrain (Fig. 6b) which are rather the same as for other alloys (compare Figs. 2b and 4b). However, for

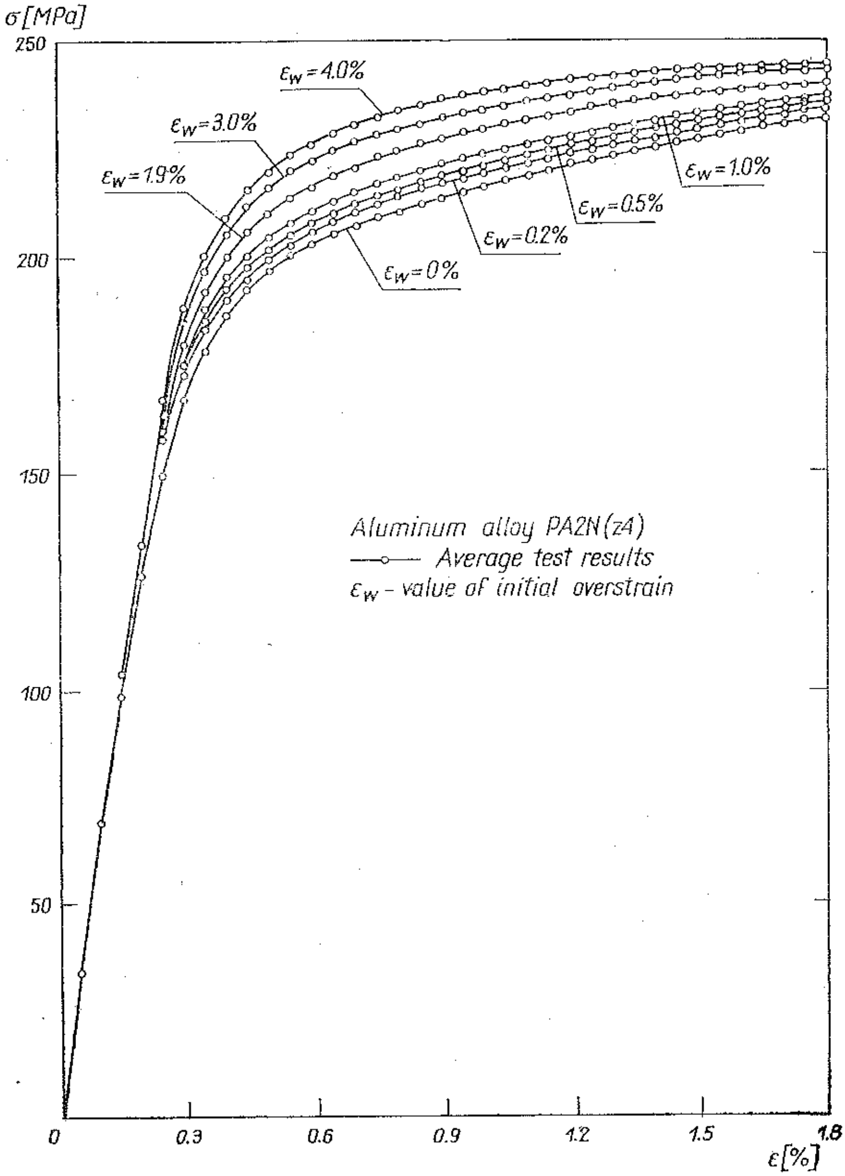

FIG. 5.

PA2N alloy the value of BEF is distinctly higher. It shows that such an approach to the Bauschinger effect does not fully describe the phenomenon.

The author also has to admit that the results of different compressive tests [3] carried out for another batch of the PA2N aluminum alloy show that the Bauschinger effect occurs in a similar way as for PA7N and PA4N alloys. It is difficult to ansver with certainty what the reason is for the different influence of initial overstrain on the mechanical properties for two different batches of the same kind of material.

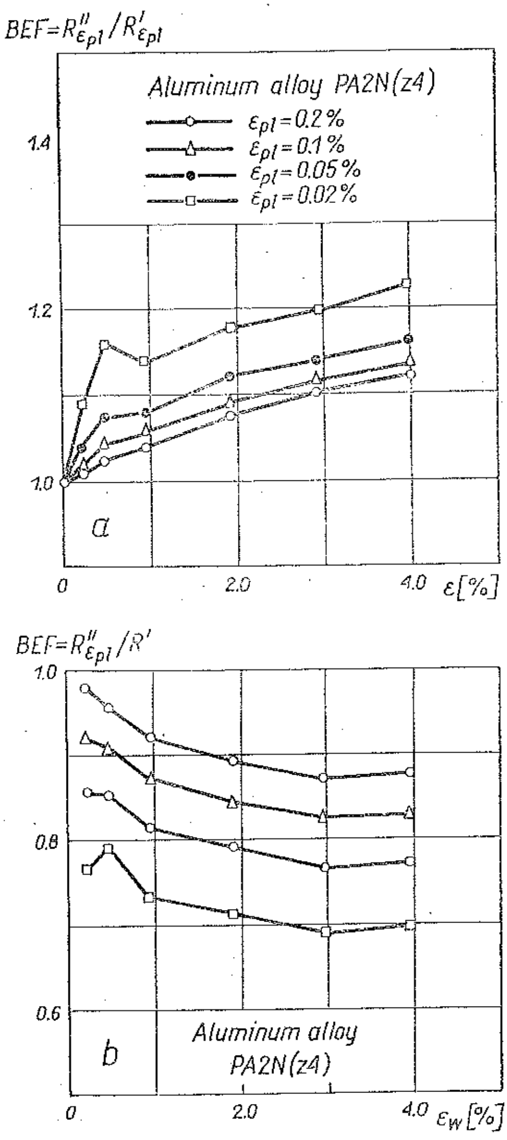

FIG. 6.

It seems, however, that some explanation of this problem can be found in the process of age-hardening. The material used for investigation of the Bauschinger effect was stored in the laboratory for about 10 years and perhaps this is why large differences between tensile and compressive stress-strain curves were observed (see Table 2). Such differences were not observed for other tested materials. Of course, different conditions of production for both batches of material can have a significant influence as well. An exact explanation of that problem requires special investigations including structure tests and also taking into account the technological and rheological processes. Of course, this was beyond the programme of this paper and can be an interesting subject for further investigation. During the above mentioned studies [3] the author also observed that for a nonhomogeneous material showing large differences in the distribution of permanent strain during the process of overstraining, strain-hardening does not occur with loading in the direction reverse to the initial overstrain, and the Bauschinger effect increases with an increasing value of initial overstrain.

For all tested aluminum alloys the influence of initial tensile overstrain on the value of the modulus of elasticity was not observed but this problem needs further investigations using a more accurate technique of measuring strains. It is necessary to admit that such a problem has been the subject of numerous experimental works [18, 19, 20] but their results lead to different conclusions and do not give an unambigous answer.

4. Conclusions and final remarks

Test results show the differences between two of the most common approaches in defining the magnitude of the Bauschinger effect. Both approaches are of importance from the practical point of view but in the author's opinion the Bauschinger effect factor (BEF) computed by the formula (1.1) is more accurate and describes the phenomenon in such a way as it was understood by its discoverer J. Bauschinger.

The Bauschinger effect in structural metals may have a diverse character. Essential differences may not only occur in various kinds of material but also within the same alloy.

Results of experiments obtained for aluminum alloys PA7N and PA4N seem to be characteristic of aluminum alloys which have very close stress-strain curves in tension and in compression and the ability of uniform overstraining. In such a case the magnitude of BEF computed by two approaches depends on the value of the permanent strain (ε_{pl}) used in obtaining the yield strength. The Bauschinger effect increases with a decrease of the value ε_{pl}. Hence the necessity of defining the offset when giving values of the BEF, just as it is necessary to state a conventional offset yield strength for a given material. Maximum decrease of compressive yield strength $R''_{\varepsilon_{pl}}$ appeared for the initial tensile overstrain at about 0.5–1% and it is not dependent on the value of ε_{pl}. With a further increase of the initial overstrain the value of the BEF computed by the formula (1.1) starts to increase (the Bauschinger effect gradually disappears). The BEF computed by the formula (1.2) decreases in magnitude with increasing initial overstrain up to approximately 2 percent and thereafter it becomes effectively constant and depends only the value of ε_{pl}.

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Received February 17, 1983.