Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 6, 2000

DYNAMIC DEFORMATION OF ALUMINUM ALLOY AMg-6 AT NORMAL AND HIGHER TEMPERATURES

B. L. Glushak, O. N. Ignatova, V. A. Pushkov, S. A. Novikov, A. S. Girin, and V. A. Sinitsyn

UDC 536.71

Dynamic deformation of AMg-6 *alloy in uniaxial extension and compression at strain rates of* $\dot{\varepsilon} = 190$–1450 sec^{-1} *at test temperatures of* 25–250°C *is studied experimentally. A phenomenological constitutive equation that agrees with experimental data is constructed within the framework of the elastoplastic model of a deformable solid.*

Aluminum alloy AMg-6 is widely used in various areas of present-day engineering. However, its properties have been studied mainly under static loading [1–3]. The existing experimental data on the behavior of this alloy are fragmentary and were obtained at normal temperature [4, 5].

1. Technique and Results of Tests. To obtain dynamic diagrams of uniaxial extension and compression, we used the method of Hopkinson's sectional rod (HSR) [6]. The specimens were loaded by a horizontal impact machine. A 4-kg striker was accelerated by the impact machine and then it was decelerated by a special damper to generate a pulse load in the loading rod which was further transferred to the specimen. In higher-temperature tests, the specimens were clamped between the ends of two rods and heated together with the rods. For this purpose, a special portable electric heater with a power of about 1 kW was used. In this case, heating the rod ends to 300–400°C changes the elastic properties of the rod material (steel) insignificantly and, hence, it does not decrease the accuracy of the HSR method [7]. To obtain a homogeneous temperature field in the specimens, the latter were maintained at a given temperature, which was measured by chromel-copel thermocouples, for 4–6 min.

In dynamic-compression tests, we used a loading rod of diameter 12 mm and length 1500 mm and a supporting rod of diameter 12 mm and length 600 mm from hardened steel 30KhGSA. The specimens were shaped like continuous cylinders of diameter 8 mm and height 8 mm.

In dynamic-extension tests, the loading rod was the same, whereas the supporting rod was a hollow cylinder (outer diameter 20 mm, inner diameter 16 mm, and height 500 mm) from the same steel. The specimens to be tested were shaped like a thimble [4] with the following dimensions: diameter 20 mm and height 24 mm (thickness of the working part was 2 mm). The specimens to be tested in compression and tension were fabricated from AMg-6 bars in the supply state.

The primary deformation diagrams were recalculated to obtain the stress intensity–strain intensity relationships (σ_i–ε_i) with the use of the well-known procedure [8].

The dynamic-compression experiments were performed at $T = 25$, 150, and 250°C with strain rates of $\dot{\varepsilon} = 190$–1400 sec^{-1}.

The dynamic-extension experiments were performed at $T = 25$°C with strain rates of $\dot{\varepsilon} = 640$–1450 sec^{-1}. Since it was difficult to control the temperature of the working part of the specimen clamped

Institute of Experimental Physics, Sarov 607190. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 6, pp. 139–143, November–December, 2000. Original article submitted January 20, 1999; revision submitted December 20, 1999.

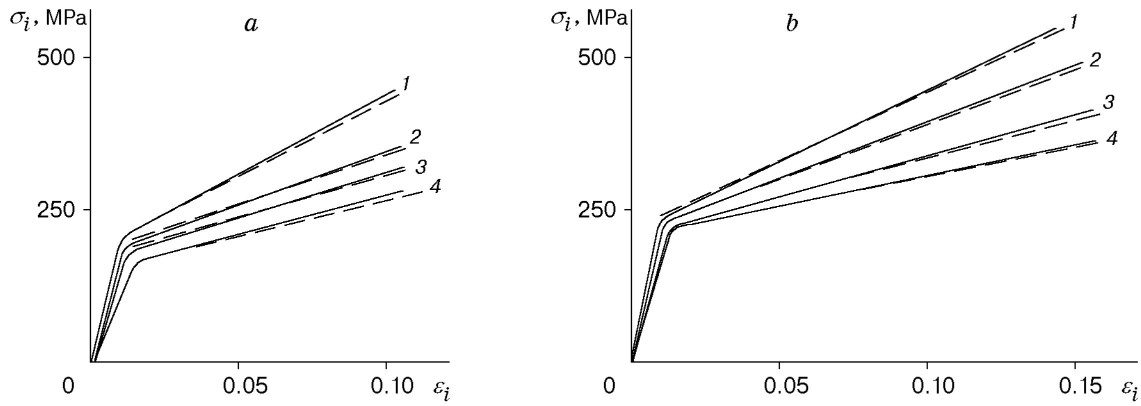

Fig. 1. Typical compression and extension diagrams for AMg-6 at T = 298, 423, and 523 K (curves 1–3, respectively) and the extension diagrams at T = 298 K (curves 4): solid and dashed curves refer to calculation and experiment, respectively; (a) $\dot{\varepsilon}$ = 250–550 (1), 360–620 (2), 190–530 (3), and 640–800 sec^{-1} (4); (b) $\dot{\varepsilon}$ = 1100–1300 (1), 1020–1300 (2), 1200–1450 (3), and 1200–1450 sec^{-1} (4).

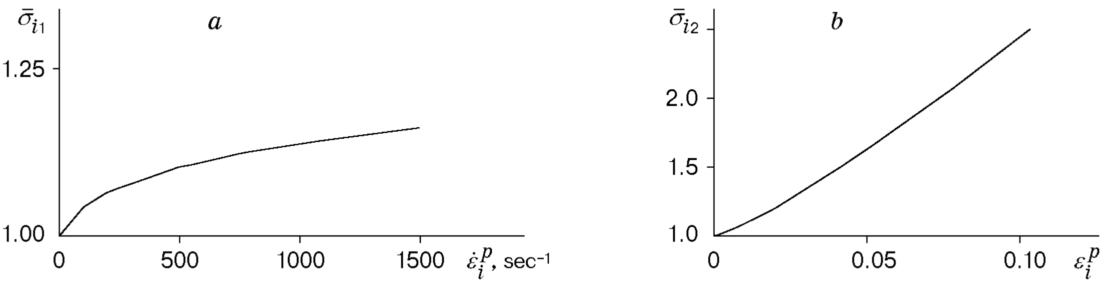

Fig. 2. Stress intensity $\bar{\sigma}_{i1}$ versus the intensity of plastic strain rate $\dot{\varepsilon}_i^p$ (a) and the stress intensity $\bar{\sigma}_{i2}$ versus plastic strain ε_i^p (b).

coaxially between the loading and supporting rods, the dynamic-extension experiments at higher temperatures were not performed.

The dynamic-compression experiments with AMg-6 show that, an increase in the strain rate $\dot{\varepsilon}$ from 190–620 to 1020–1400 sec^{-1} at 25, 150, and 250°C increases the yield point $\sigma_{-0.2}$ by 10–12% (see Table 1) ($\hat{\sigma}_{\pm 0.2}$ is the average value of the yield point). Moreover, for the above-mentioned ranges of $\dot{\varepsilon}$ variation, the quantity $\sigma_{-0.2}$ decreases by 18–20% as the temperature increases from 25 to 250°C.

The dynamic-extension experiments for AMg-6 show that an increase in the strain rate $\dot{\varepsilon}$ from 640–800 to 1200–1450 sec^{-1} increases the yield point $\sigma_{+0.2}$ by approximately 11% (see Table 1). In the process, only one specimen failed with $\dot{\varepsilon}$ varied within 640–800 sec^{-1}; in the range of 1200–1450 sec^{-1}, all the specimens failed. For the first range of $\dot{\varepsilon}$, the ultimate strength is $\sigma_{+B} = 310$ MPa, the residual elongation in extension is $\delta = 14\%$ and it is $\sigma_{+B} = (338.3 \pm 16.4)$ MPa and $\delta = (22.0 \pm 1.8)\%$ $(p = 0.95)$ for the second range of $\dot{\varepsilon}$. It follows from these data that, for $T = 25$°C and the same $\dot{\varepsilon}$, the compressive yield point is higher than the tensile yield point: $\sigma_{-0.2} > \sigma_{+0.2}$. This discrepancy between the tensile and compressive yield points is typical of many materials. The results of this work agree satisfactorily with the data of [4, 5].

2. Constitutive Equation for AMg-6. We consider aluminum alloy AMg-6 as an elastoplastic medium for which the stress intensity σ_i (the yield point for uniaxial stresses) depends on the following four main variables which characterize its stress-strain state: the plastic strain intensity ε_i^p, the intensity of plastic strain rate $\dot{\varepsilon}_i^p$, the pressure P, and the current temperature T [9, 10], i.e., $\sigma_i = \sigma_i(\varepsilon_i^p, \dot{\varepsilon}_i^p, P, T)$.

In the simplest case, σ_i is written in the form of a product of four simple functions, each of which depends on one parameter [10]:

$$\sigma_i = A f_1(\varepsilon_i^p) f_2(\dot{\varepsilon}_i^p) f_3(P) f_4(T). \qquad (1)$$

Here the function f_1 describes the strain hardening, the functions f_2 and f_3 take into account the effect of the intensity of plastic strains and the pressure, respectively, and the function f_4 describes the thermal loss

TABLE 1

Type of loading	T, °C (T, K)	$\dot{\varepsilon}_i^p$, sec^{-1}	$\sigma_{\pm 0.2}$, MPa (experiment)	$\hat{\sigma}_{\pm 0.2}$, MPa (experiment)	$\sigma_{\pm 0.2}$, MPa (calculation)
Compression	25 (298)	420 520 250 550	190 175 200 190	188.8 ± 16.5	197
Compression	25 (298)	1210 1100 1290 1300 1130	210 215 200 215 210	210 ± 7.7	207
Compression	150 (423)	620 360 590 590 430	180 170 170 160 168	169.6 ± 8.9	177
Compression	150 (423)	1170 1080 1300 1020 1120	175 190 195 185 205	190 ± 14	184
Compression	250 (523)	240 190 530 200	153 155 170 160	159.5 ± 12.2	154
Compression	250 (523)	1200 1400	170 180	175	165
Extension	25 (298)	800 800 770 640	142 138 145 140	141.3 ± 4.8	146
Extension	25 (298)	1450 1350 1200 1420	160 155 150 160	156.3 ± 7.7	151

of strength. The analytic form of the functions f_i and the numerical values of the parameters which enter these functions are determined experimentally.

We write expression (1) in the form

$$\sigma_i = A[1 + a(\varepsilon_i^p)^n]\Big[1 + b\Big(\ln \frac{\dot{\varepsilon}_i^p}{\dot{\varepsilon}_{i0}^p}\Big)^m\Big]\Big[1 + c\Big(\frac{T}{T_{\text{melt}}}\Big)^k\Big](1 + \alpha P), \tag{2}$$

where A, a, b, c, n, m, k, and α are constants, $\dot{\varepsilon}_{i0}^p = 1$ sec^{-1} is the normalizing quantity, T [K] is the current temperature, and $T_{\text{melt}} = 933$ K is the melting point. The constants determined from the compression experiments are as follows: $A = 200$ MPa, $a = 22.85$, $n = 1.2$, $b = 5 \cdot 10^{-4}$, $m = 2.9$, $c = -0.8$, $k = 2$, and $\alpha = 3.5 \cdot 10^{-5}$ MPa^{-1}. For extension, we have $A = 145$ MPa.

The experimental data and calculation results obtained from formula (2) are summarized in Table 1 and shown in Fig. 1. The discrepancy between the experimental and calculated data does not exceed 10%, which is within the experimental error.

Using (2), one can obtain relations between the dimensionless stress intensity $\bar{\sigma}_{i1} = \sigma_i/\sigma_{i1}$ and the intensity of plastic strain rate $\dot{\varepsilon}_i^p$ (Fig. 2a) and relations between $\bar{\sigma}_{i2} = \sigma_i/\sigma_{i2}$ and the plastic-strain intensity ε_i^p (Fig. 2b) ($\sigma_{i1} = \sigma_i$ for $\varepsilon_i^p = \varepsilon_{i0}^p$, $T = \text{const}$, $P = \text{const}$, and $\varepsilon_i^p = \text{const}$; $\sigma_{i2} = \sigma_i$ for $\varepsilon_i^p = 1\ \text{sec}^{-1}$, $T = \text{const}$, $P = \text{const}$, and $\dot{\varepsilon}_i^p = \text{const}$).

One can see from Fig. 2 that the effect of the intensity of plastic-strain rate $\dot{\varepsilon}_i^p$ on hardening of aluminum alloy AMg-6 is negligible, whereas the effect of the strain hardening ε_i^p is significant.

It is known that, under static loading, an increase in the temperature of aluminum alloys decreases the plastic-strain resistance of the body [11]. This tendency is also observed under dynamic loading (see Table 1).

This work was partially supported by the Russian Foundation for Fundamental Research (Grant No. 001-01-0052).

REFERENCES

1. R. E. Shalin, *Aviation Materials: Handbook* [in Russian], Vol. 4, Part 1, ONTI–VIAM, Moscow, (1982).
2. B. N. Arzamasov, I. I. Sidorin, G. F. Kosolapov, et al., *Materials Science* [in Russian], Mashinostroenie, Moscow (1986).
3. A. P. Zolotorevskii, *Structure and Strength of Cast Aluminum Alloys* [in Russian], Metallurgiya, Moscow (1981).
4. A. P. Bol'shakov, S. A. Novikov, and V. A. Sinitsyn, "A study of the dynamic diagrams of uniaxial extension and compression of copper and AMg-6 alloy," *Probl. Prochnosti*, No. 10, 87–88 (1979).
5. V. Gloushenkov, R. Novobratsky, and A. Bourmistrov, "Influence of the spread in values of aluminum alloy dynamic properties upon the results of magnetic-pulse strain," in: *Proc. of the Conf. DYMAT-91* (Oct. 14–18, 1991, Strasbourg, France) (1991), pp. c3/331–c3/334.
6. V. P. Muzychenko, S. I. Kaschenko, V. A. Gus'kov, "Application of Hopkinson's sectional rod to investigation of the dynamic properties of materials: Review," *Zavod. Lab.*, No. 1, 58–66 (1986).
7. L. P. Loshmanov, O. A. Nechaeva, and V. D. Rudnev, "High-rate tests at elevated temperatures," *Zavod. Lab.*, No. 5, 40–42 (1996).
8. N. N. Malinin, *Applied Theory of Plasticity and Creep* [in Russian], Mashinostroenie, Moscow (1975).
9. B. L. Glushak and O. N. Ignatova, "An elastoplastic model of dynamic deformation of U-238 and its alloy with Mo," *Vopr. Atom. Nauki Tekh., Ser. Mat. Model. Fiz. Prots.*, No. 2, 45–49 (1998).
10. L. M. Meyer, "Constitutive equation at high strain rates," in: M. Meyers, L. Murr, and K. Standhammer, *Shock-Wave and High-Strain-Rate Phenomena in Materials*, Mareel Dekker, New York–Basel–Hong Kong (1992), pp. 49–68.
11. I. S. Grigor'eva and E. Z. Meilikhova (eds.), *Physical Quantities* [in Russian], Énergoatomizdat, Moscow, (1991).