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Letter to the Editors

Compression properties of lead–bismuth

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Abstract

The mechanical properties of a lead–bismuth alloy were studied by compression testing at different temperatures between 20 and 112 °C with strain rates from 10^{-3} to 10^{-6}/s. The results indicate that the yield strength depends strongly on both temperature and strain rate. The yield stress is linearly proportional to the logarithms of strain rate at constant temperature. The yield stress can be fit with a second order polynomial of temperature at constant strain rate. With these fittings the yield stress can be fairly estimated for any temperature and strain rate in the present temperature and strain rate ranges.

1. Introduction

As one of the key projects in the R&D program of accelerator driven systems (ADS) for the transmutation of nuclear waste, a mega watt pilot (MEGAPIE) target is being studied and developed at the Paul Scherrer Institute, Switzerland under a worldwide collaboration [1,2]. Liquid Pb–Bi (45 wt% Pb and 55 wt% Bi) will be used as the target material to produce spallation neutrons. To simplify target handling after irradiation, it is strongly intended to solidify the liquid Pb–Bi and maintain it in the target. However, it is known that the volume of Pb–Bi will shrink first and then expand after solidification [3–5]. This phenomenon raises up the question whether the Pb–Bi container will break or deform after Pb–Bi solidifying. This question is very important because firstly it is related to the safety issue for the target handling after irradiation, and secondly for the post-irradiation examinations on the container, it is necessary to know whether the container is deformed. In order to answer this question, a delicate calculation has to be performed. Since the Pb–Bi will be subjected to compression by the container during expansion, the compression properties of solid Pb–Bi in a wide temperature range (20 °C to the melting point temperature, 125 °C) are required. However, except for few data of compression tests at room temperature [3], no other data could be found in the literature. Therefore, in the present work a series of compression tests have been performed at different temperatures between 20 and 113 °C and with different strain rates from about 10^{-6} to 10^{-3}/s.

2. Experimental

The Pb–Bi material used in this work has a composition of 45.1 wt% Pb and 54.6 wt% Bi. The content of impurities is 0.3 wt% in total, including mainly Ag, B, Cu, Fe, Na, S, Si and Sn. The samples are cylinders of 15 mm diameter and 15 mm length. For preparing these samples, a mould with four holes of 16 mm diameter and 100 mm depth was manufactured. The mould was first heated up to about 150 °C in air. Then small pieces of Pb–Bi were put into the holes until they were fully filled. The Pb–Bi alloy was further heated to about 190 °C then cooled down gradually from bottom to top. In about 50 min, the temperature dropped to 36 °C. The mould was opened and four Pb–Bi rods of $\varnothing$ 16 × 100 mm were obtained. The rods were kept at room temperature for two weeks. Afterwards, five samples were fabricated from each rod with a lathe machine.

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A small set-up was manufactured and installed in a Zwick 10 kN mechanical testing machine to carry out the compression tests. The samples were heated up in oil so that no oxidation could occur during testing. The oil improved also the homogeneity of the temperature distribution in the sample. However, due to the small size of the heater, the difference of temperature between the top and the bottom of a sample was about 2 °C. The testing started about 30 min after the temperature had stabilized. The tests were conducted with constant cross-head speeds ranging from 1.0 μm to 0.9 mm/min, which give the nominal strain rates from 1.1×10^{-6} to 10^{-3}/s. Due to the compliance of the system, the real strain rates in the elastic deformation part were about half of the nominal values. For simplicity only the nominal strain rates will be used in the text below. The displacement was measured by the cross-head travel and corrected with the compliance calibrations.

Table 1
Yield stress (YS) and maximum compression stress (UCS) under different test conditions

Test no.	Temperature (°C)	Strain rate (1/s)	YS (MPa)	UCS (MPa)
1	20	10^{-3}	40.3	53
2	52	10^{-3}	26.2	33.8
3	71	10^{-3}	18.3	23.5
4	95	10^{-3}	11.5	13.7
5	111	10^{-3}	8.0	9.4
6	20	10^{-4}	32.3	27
7	94	10^{-4}	7.0	8.5
8	20	10^{-5}	21.3	40.3
9	50	10^{-5}	12.8	15
10	72	10^{-5}	6.9	8.1
11	93	10^{-5}	4.1	5
12	113	10^{-5}	2.5	2.8
13	20	1.1×10^{-6}	12.1	15
14	94	1.1×10^{-6}	2.0	2.3
15	111	1.1×10^{-6}	1.1	1.2

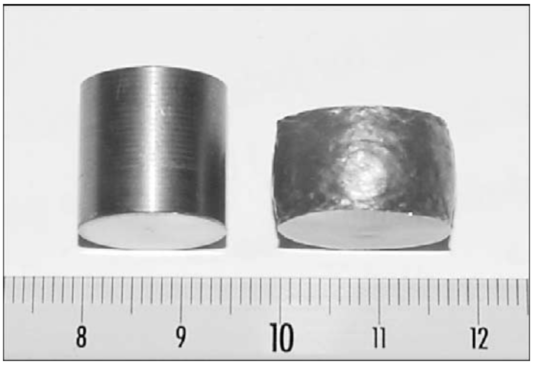

Fig. 1. The photograph shows a sample before testing and a sample after 3 mm compression.

In order to obtain the temperature and strain rate dependences of yield stress, total 15 tests were performed at five different temperatures and four strain rates. The test conditions can be seen in Table 1. Most of tests were terminated at a displacement of either 2 or 3 mm. Some tests at the lowest strain rate of 1.1×10^{-6}/s were terminated at 1mm. Fig. 1 shows a sample before testing and a sample after 3 mm compression.

3. Results and discussion

The compression properties of Pb–Bi show a strong dependence on temperature and strain rate under the present testing conditions. Fig. 2 presents the engineering stress–strain curves of two sets of tests performed at different temperatures with strain rate of 10^{-3}/s while Fig. 3 gives the stress–strain curves of tests with different strain rates at 20 °C. The compression stress depends strongly on the testing temperature. For example, in Fig. 2 the maximum compression stress changes from 9.4 MPa at 112 °C to 53 MPa at 20 °C at a strain rate of 10^{-3}/s. This figure also illustrates that the change rate of the maximum stress increases with decreasing temperature. The curves in Fig. 3 show that the maximum compression stress decreases abruptly with decreasing strain rate. The few data of compression tests at room temperature presented in Ref. [3], namely compression stresses of 22.5/32.1, 28.4/38.4 and 27.8/38 MPa at 0.2%, 1% and 10% compression strains respectively, are close to our data at strain rates 10^{-5} and 10^{-4}/s presented in Fig. 3.

Yield stresses (YS) have been evaluated from all the stress–strain curves at 0.2% strain offset, which are listed in Table 1 together with the maximum compression stresses (UCS). Fig. 4 illustrates the temperature

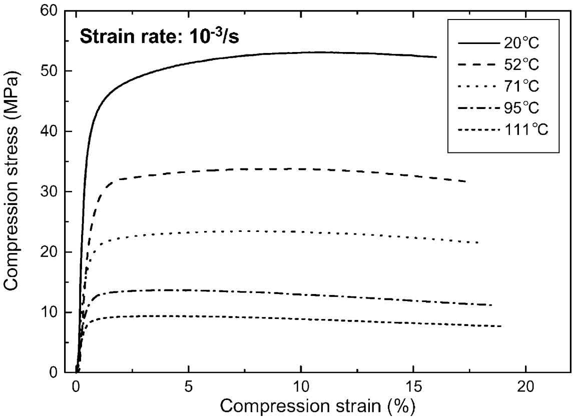

Fig. 2. Compression stress–strain curves of Pb–Bi tested at different temperatures with a strain rate of 10^{-3}/s.

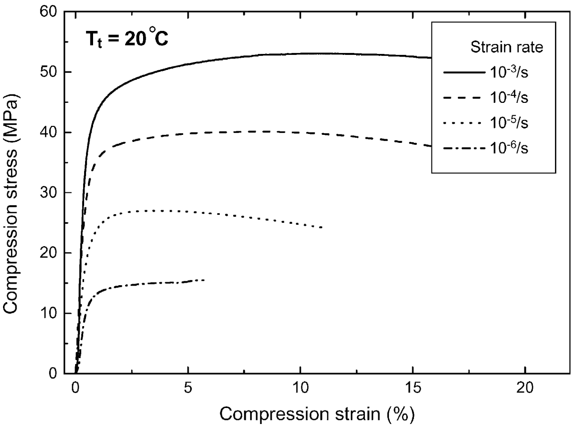

Fig. 3. Compression stress–strain curves of Pb–Bi tested at 20 °C with different strain rates.

dependence of yield stress at three different strain rates, 10^{-3}, 10^{-5} and 1.1×10^{-6}/s. The data from each strain rate can be well fit with a simple polynomial form, as demonstrated in the figure. The fitting has taken the zero stress at the melting temperature point into account. The strain rate dependence of the yield stress is plotted in Fig. 5. The data from each temperature can be fit with a linear form. With the fittings presented in Figs. 4 and 5, the yield stress at any temperature between 20 and 115 °C and any strain rate between 10^{-3} and 10^{-6}/s can be figured out with reasonable accuracy. For example, the yield stress at 80 °C and 5×10^{-5}/s is estimated to be around 9.5 MPa.

From the stress–strain curves of 10^{-3}/s strain rate, the elastic modulus at each temperature was calculated. Fig. 6 shows the temperature dependence of the elastic modulus. Since the cross-head travel could not represent the real displacement even after correction, the uncertainty of the elastic modulus value can be large. Nevertheless, these values could be taken as a reference. A more precise determination is considered.

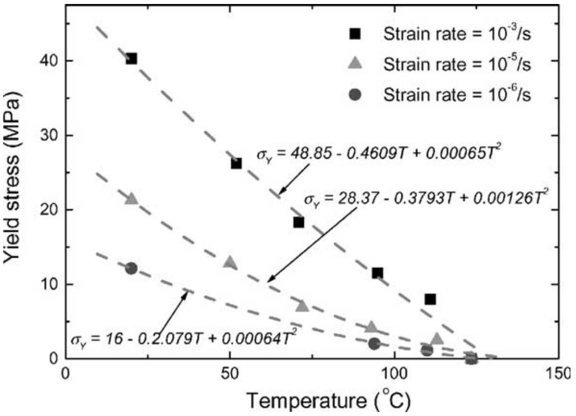

Fig. 4. Temperature (T) dependence of yield stress (σ_y) at different strain rates. Zero yield stress at the melting temperature is taken into account for fitting the data.

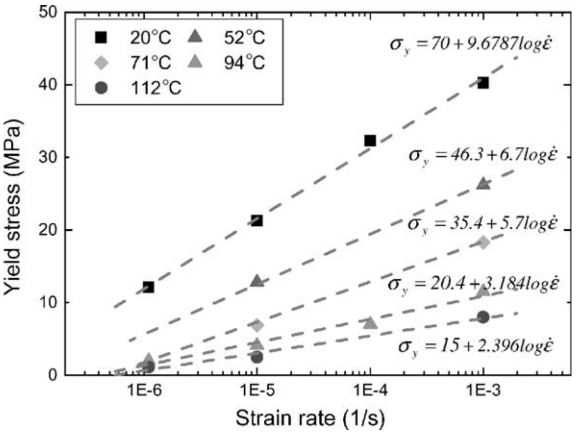

Fig. 5. Strain rate ($\dot{\varepsilon}$) dependence of yield stress (σ_y) at different temperatures.

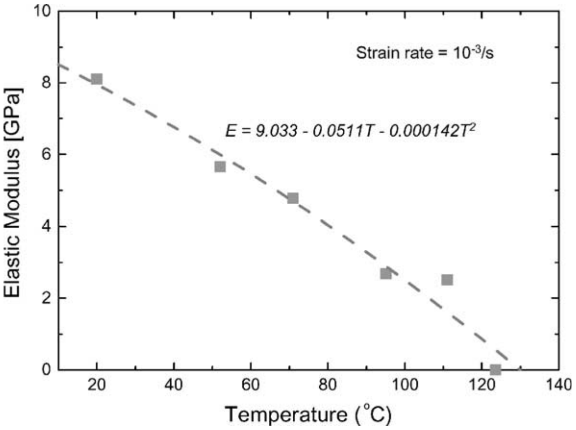

Fig. 6. Temperature (T) dependence of the elastic modulus (E) derived from stress–strain curves of 10^{-3}/s strain rate.

From the present results it is clear that the MEGAPIE target has to be cooled down as slowly as possible after irradiation, so that the stress can be controlled at a low level without the break of the Pb–Bi container.

4. Conclusion

Compression tests have been performed on solid Pb–Bi at different temperatures between 20 and 112 °C with different strain rates of 10^{-3} to 1.1×10^{-6}/s. The results demonstrate that the yield strength of Pb–Bi depends strongly on temperature and strain rate. The yield stress is linearly proportional to the logarithms of strain rate at constant temperature. The yield stress can be fit with a second order polynomial of temperature at constant strain rate. With these fits, yield stresses can be calculated at any conditions in the present temperature and strain rate ranges. The present results suggest that MEGAPIE target should be cooled down as slowly as possible to avoid breaking the Pb–Bi container.

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