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# Effects of strain rate on tensile properties of TZM and Mo–5%Re

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## Abstract

In the present work, we have studied the strain rate sensitivity of tensile properties of TZM and Mo–5%Re alloys. Tests were performed at room temperature and around the transition temperature of each alloy, at strain rates varying over five decades. Ductility appeared insensitive to strain rate, whereas the strength is found to be strain rate dependent. Both proof stress and ultimate tensile strength are affected by strain rate and the Mo–5%Re alloy is more sensitive than TZM. As expected, the hardening decreases with temperature; in TZM alloy the strain rate sensitivity was apparent only at room temperature.

## 1. Introduction

A previous article [1] showed very high ductile-to-brittle transition temperatures (DBTTs) of TZM and Mo–5%Re, as measured by impact testing unirradiated samples. These DBTTs were quite different from the values determined by taking into account the reduction of area or the deflection of bent specimens. Moreover, mechanical properties of molybdenum alloys are known to be sensitive to testing parameters.

High atomic number metals like tungsten, niobium or molybdenum alloys are still appealing as structural materials for those parts of a magnetic fusion reactor (MFR) which are exposed to high heat fluxes, especially for the divertor [2]. These refractory alloys have drawn the designers' attention owing to their thermo-mechanical properties (e.g. the high thermal factor, $\lambda\sigma/\alpha E$, deriving from the high thermal conduction $\lambda$, the good mechanical strength $\sigma$, the very low thermal expansion $\alpha$), despite their poor toughness.

Ductility, as measured by tensile tests, is not a good measure of the brittleness of these materials. For example, total elongation of Mo alloys is always higher than 10–12%, and reduction of area rarely drops below 70%. Taking into account just these quantities, it could be reasonable to consider Mo alloys not more brittle than many others widely used structural materials, like martensitic steels, precipitation hardened (PH) or oxide dispersion strengthened (ODS) steels.

Nevertheless, even in their optimised metallurgical state, the deformed and stress-relieved (DSR) condition, precipitation or solid–solution hardened Mo alloys have demonstrated a low fracture resistance ($K_c \approx 20$–40 MPa $\sqrt{\mathrm{m}}$), a very high ductile-to-brittle transition temperature (DBTT) and impact resistances at room temperature as low as 2–8 J/cm$^2$ [1,3–5]. Moreover, the behaviour of this family of materials is seriously affected by loading rate [6] and loading state (multiaxiality promoted by notches). Since the effects of strain rate on tensile properties of Mo alloys are relatively unknown, at least from a quantitative standpoint, we have addressed a part of our experimental activity to supply

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designers with data useful to fulfil, even if partially, this knowledge.

## 2. Materials and experimental details

Table 1 reports the chemical compositions of the Mo alloys investigated. The materials have been produced by Plansee GmbH (formerly Metallwerk Plansee GmbH, Reutte, Austria), using powder metallurgy (PM) processes of pressing, sintering, forging, hammering, extrusion or hot/warm drawing.

Before polishing and final mechanical machining, the rods were submitted to a stress-relief heat treatment in a hydrogen atmosphere; unfortunately neither the treatment duration nor temperature is known. The final metallurgical state is referred to as DSR condition.

Grain sizes (cross-section) <10 μm for TZM and <20 μm for Mo–5%Re were reported by Plansee. A discrepancy exists between the supplier's data and our measurements. Metallographic observations revealed the classic microstructure of highly deformed materials: that is, grains elongated along the main drawing direction. Typical grain size along the principal axis of specimens was of the order of 180–200 μm (TZM) and 210–240 μm (Mo–5%Re) whereas transverse dimensions were, respectively, ≈35 μm and ≈88 μm and grain aspect ratios (GARs) were ≈5.5 and ≈2.6. Vickers hardness (10 kgf) of TZM was of the order of (275 ± 15) kg/mm$^2$; the corresponding value for the Mo–5%Re alloy was (210 ± 10) kg/mm$^2$.

Specimens were machined by turning; they had 8-mm threaded ends, a 4.5-mm diameter cross-section and a parallel gauge-length of 22.5 mm ($L_0 = 5.65\sqrt{S_0}$), with the roughness of gauge section ($R_a$) lying between 1 and 1.5 μm. Tensile tests were carried out using a closed-loop electro-mechanical Mayes ESM 100 load frame. The machine was controlled by the actual position of the moving crosshead, an external LVDT providing the feedback signal regardless of loading-train compliance. The selected strain rate was kept constant up to the fracture of the specimen. Nominal initial displacement rates covered a range from $1 \times 10^{-1}$ to $1 \times 10^{-5}\,\mathrm{s}^{-1}$. The fastest test had a duration of 1.5 s (TZM), the longest reached a testing time of 15.2 h (Mo–5%Re). The temperature was monitored by means of a K-type thermocouple and ranged from RT to around the transition temperature as measured by the impact tests. All experiments were carried out in air.

## 3. Results and discussion

Mechanical properties were determined from digitalised load–displacement curves. Mean tensile properties are summarised in Tables 2 and 3. Some isothermal stress–strain curves (engineering data) have been reported in Figs. 1 and 2. These plots clearly show the insensitivity of Young's modulus to strain rates for $\dot{\varepsilon} \leqslant 0.1\,\mathrm{s}^{-1}$. The same figures illustrate the influence of testing parameters on tensile plastic flow. TZM showed a very early mechanical instability (low uniform elongation) in all testing conditions. However, low uniform elongation was exhibited in Mo–5%Re only at room temperature and for deformation rates higher than $1 \times 10^{-5}\,\mathrm{s}^{-1}$; this result is not consistent with previous data [1].

Both ultimate tensile and 0.2% proof stresses increase linearly with the logarithm of the strain rate (see Fig. 3). Such a systematic dependence was not found for the ductility. From a qualitative point of view, increasing loading rate produced a loss of ductility only at room temperature. This trend was found in both alloys.

Fig. 3 reports a plot of UTSs versus the logarithm of the strain rate. Mo–5%Re shows a sensitivity to strain rate that is highest at room temperature but is still present at 300 °C, whereas the strain rate effect on UTS of TZM appears to be significant only at room temperature or, perhaps, limited to $T \leqslant 350$ °C. As a general remark, TZM confirmed its higher strength and lower ductility, but this result is not coherent with data recently published, some authors found an inversed behaviour [7].

At the 'standard' strain rate of $1 \times 10^{-3}\,\mathrm{s}^{-1}$, the mechanical strength, at RT, appear more or less equivalent

Table 1
Chemical composition of Mo alloys (wt%, producer's guaranteed values)

| Alloy | C | Fe[a] | H[a] | Mo | N[a] | O | P[a] | Re | S[a] | Ti | W | Zr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TZM | 0.025 | 30 | <5 | Balance | <5 | 0.025 | 5 | – | 5 | 0.5 | 0.01 | 0.08 |
| Mo–5%Re | <0.03 | <100 | <5 | Balance | <10 | 0.05 | <20 | 4.75 | <20 | 0.001 | 0.03 | – |

[a] Amount quantified in ppm.

Table 2
Mean tensile properties and related standard deviation of TZM alloy, for various strain rates. Initial $\dot{\varepsilon}$ (1/s): ratio between actuator speed and gauge-length of the specimen; $R_m$ (MPa): ultimate tensile stress; $R_{p0.2}$ (MPa): 0.2% proof stress; $A$ (%): total elongation; $A_g$ (%): uniform elongation; $Z$ (%): reduction of area

| $T$ (°C) | Initial $\dot{\varepsilon}$ (1/s) | $R_m$ (MPa) | $R_{p0.2}$ (MPa) | $A$ (%) | $A_g$ (%) | $Z$ (%) |
|---|---|---|---|---|---|---|
| RT | 0.00001 | 746 ± 18.4 | 700 ± 6.4 | 34.35 ± 0.35 | 0.6 ± 0.1 | 73.8 ± 0.42 |
| | 0.0001$^{*}$ | 778 ± 7.5 | 740 ± 13 | 34.2 ± 1.9 | 0.56 ± 0.15 | 47.3 ± 19 |
| | 0.001$^{**}$ | 855 | 816 | 37.2 | 0.6 | 68 |
| | 0.01 | 914 ± 11.3 | 883 ± 11.3 | 36.2 ± 1.3 | 0.5 ± 0.1 | 70.5 ± 0.07 |
| | 0.1 | 991 ± 5.6 | 949 ± 57.9 | 28.1 ± 2.1 | 0.5 ± 0.15 | 73.4 ± 0.5 |
| 350 | 0.00001 | 631 ± 4.9 | 583 ± 55 | 13.3 | 0.4 ± 0.1 | 75 ± 05 |
| | 0.0001 | 607 ± 19.8 | 603 ± 18 | 13.8 ± 0.35 | 0.2 ± 0.1 | 75.6 ± 1.4 |
| | 0.001$^{**}$ | 626 | 610 | 13.9 | 0.3 | 75.6 |
| | 0.01 | 604 ± 15 | 597 ± 7 | 15.2 ± 0.8 | 0.25 ± 0.1 | 75.8 ± 1.5 |
| | 0.1 | 638 ± 9 | 631 ± 5 | 16 ± 0.2 | 0.27 | 77.8 ± 0.15 |
| 400 | 0.0001 | 620 ± 15 | 599 ± 17 | 13.7 ± 0.4 | 0.4 ± 0.15 | 74.7 ± 1.7 |
| | 0.001$^{**}$ | 600 | 596 | 14.4 | 0.3 | 77.3 |
| | 0.01 | 615 ± 1 | 598 ± 19 | 14.5 ± 0.3 | 0.2 ± 0.1 | 76.6 ± 0.4 |
| | 0.1 | 614 ± 11 | 610 ± 7.8 | 15.7 ± 0.4 | 0.3 ± 0.15 | 78.3 |
| 450 | 0.0001 | 594 ± 1 | 580 ± 6 | 13.6 ± 0.4 | 0.35 ± 0.15 | 75.5 ± 0.5 |
| | 0.001$^{**}$ | 560 | 541 | 12.9 | 1.2 | 74.2 |
| | 0.01 | 591 ± 12 | 586 ± 13 | 14.3 ± 02 | 0.2 ± 0.1 | 76.7 ± 1.3 |
| | 0.1 | 596 ± 2 | 580 ± 11 | 13.3 ± 0.1 | 0.25 ± 0.1 | 78.6 ± 0.6 |

Note: Mean quantities from two tests, ($^{*}$) three tests, ($^{**}$) 1 test.

Table 3
Mean tensile properties and related standard deviation of Mo–5%Re alloy, for various strain rates. Initial $\dot{\varepsilon}$ (1/s): ratio between actuator speed and gauge-length of the specimen; $R_m$ (MPa): ultimate tensile stress; $R_{p0.2}$ (MPa): 0.2% proof stress; $A$ (%): total elongation; $A_g$ (%); uniform elongation; $Z$ (%): reduction of area

| $T$ (°C) | Initial $\dot{\varepsilon}$ (1/s) | $R_m$ (MPa) | $R_{p0.2}$ (MPa) | $A$ (%) | $A_g$ (%) | $Z$ (%) |
|---|---|---|---|---|---|---|
| RT | 0.00001 | 519 ± 6 | 487 ± 3 | 56.1 ± 1 | 18.2 ± 1 | 80.8 ± 1 |
| | 0.0001 | 564 ± 4 | 533 ± 19 | 57.9 ± 2 | 0.55 ± 0.1 | 80.2 ± 0.3 |
| | 0.001$^{*}$ | 643 | 634 | 48.6 | 0.3 | 77.7 |
| | 0.01 | 712 ± 5 | 704 ± 8 | 46.2 ± 3 | 0.45 ± 0.1 | 76.4 ± 1 |
| | 0.1 | 801 ± 3 | 791 ± 9 | 36.5 ± 1.3 | 0.2 | 79.8 ± 2.4 |
| 200 | 0.0001 | 398 ± 3 | 355 ± 2 | 46.2 ± 1 | 20.7 ± 1.2 | 86.6 ± 0.3 |
| | 0.001 | 422 | 361 | 45.9 | 21.1 | 88.6 |
| | 0.01 | 431 ± 13 | 387 ± 5 | 54.7 ± 6 | 22.1 ± 2.5 | 88.3 ± 0.6 |
| | 0.1 | 456 ± 13 | 431 ± 13 | 50.8 ± 1 | 18.8 ± 2 | 87.7 ± 2 |
| | 0.00001 | 362 ± 5 | 341 | 39.3 ± 1.5 | 15.5 ± 0.1 | 90.7 ± 0.2 |
| 250 | 0.0001 | 372 ± 3 | 351 ± 8 | 40 ± 1 | 16.5 ± 2 | 91.2 ± 0.6 |
| | 0.001$^{*}$ | 391 | 359 | 44.6 | 19 | 88.7 |
| | 0.01 | 402 ± 4 | 359 ± 3 | 49.2 ± 0.4 | 20.9 ± 0.5 | 90.6 ± 1 |
| | 0.1 | 426 ± 2 | 386 ± 4 | 51.3 ± 2 | 19.6 ± 0.1 | 91.4 ± 0.5 |
| 300 | 0.0001 | 358 ± 6 | 341 ± 2 | 35.6 | 7.65 ± 10 | 92.8 ± 1 |
| | 0.001$^{*}$ | 372 | 348 | 42.5 | 17.4 | 94.1 |
| | 0.01 | 383 ± 1 | 345 ± 4 | 49.3 ± 4 | 20.1 ± 0.5 | 92 ± 0.1 |
| | 0.1 | 400 ± 3 | 358 ± 2 | 47.5 ± 1.2 | 19.4 ± 0.1 | 91.5 ± 0.6 |

Note: Mean quantities from 2 tests, ($^{*}$) 1 test.

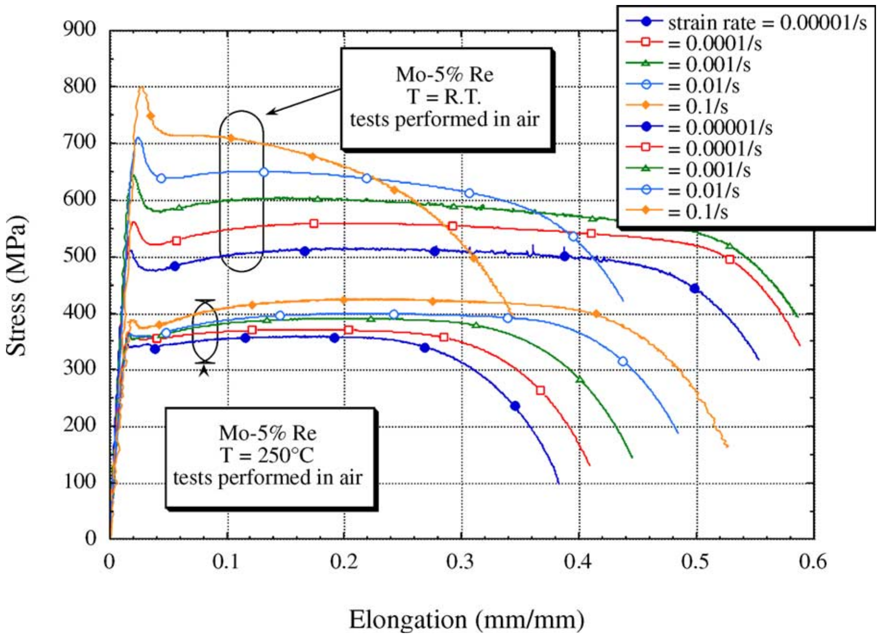

Fig. 1. Stress–strain curves of Mo–5%Re at room temperature and 250 °C.

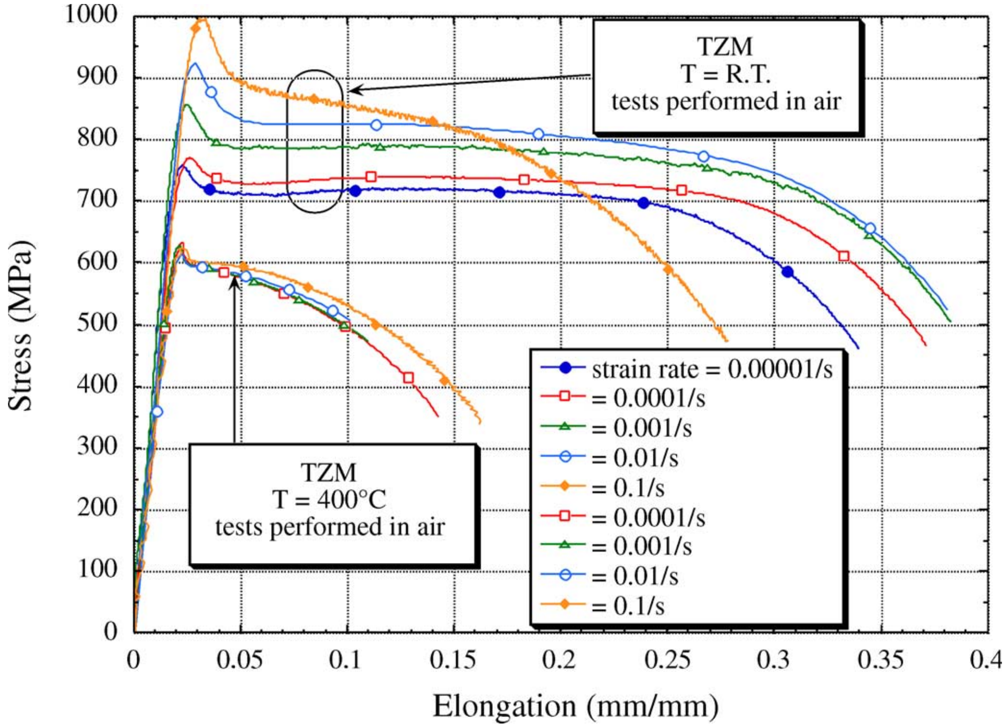

Fig. 2. Stress–strain curves of TZM at room temperature and 400 °C.

to those previously measured on different batches of the same materials, but notably inferior at higher temperature [1]. Despite the nominal identical metallurgical state (similar hardness, grain morphology and size) and chemical composition, different batches behave in a somewhat different way.

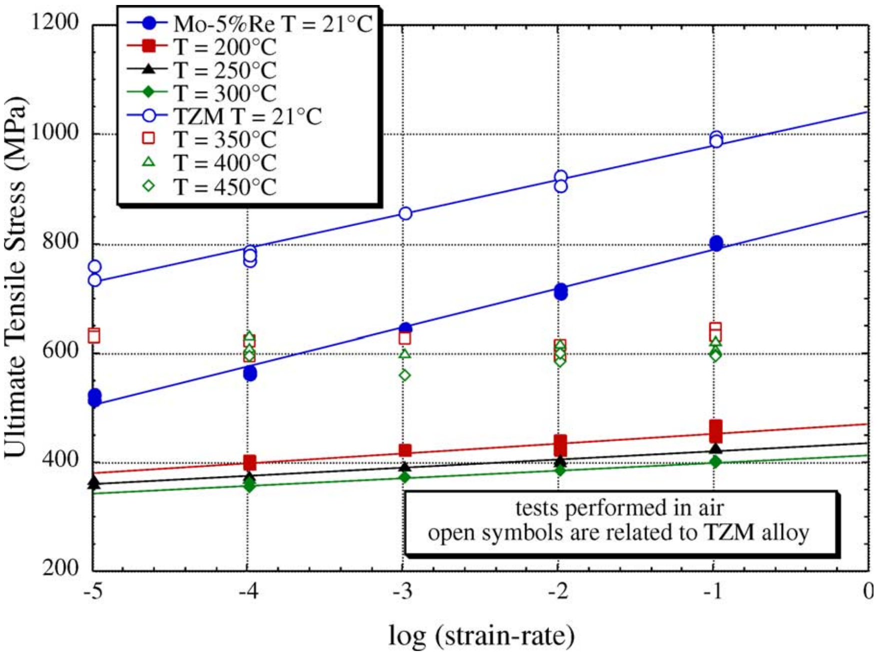

Fig. 3. Strain rate effect on ultimate tensile stress of Mo–5%Re and TZM.

## 4. Conclusion

Two Mo alloys have been studied from the standpoint of the effect of strain rate on their tensile properties. Tests were carried out at room temperature and around the transition temperature previously determined by means of impact tests. By the analysis of data, it can be stated that:

- with increasing strain rates, the strength of the solid solution strengthened alloy (Mo–5%Re) increases. Both ultimate and proof stresses increase with strain rate up to, at least, 300 °C;
- the mechanical properties of the precipitation-hardened alloy (TZM) were less sensitive to strain rate, having a lower hardening coefficient. Moreover, the increase of mechanical strength with strain rate was limited to room temperature;
- the strain rate sensitivity of strength exhibited a semi-log dependence of strength on strain rate;
- there was no apparent systematic dependence of ductility on temperature or strain rate;
- a batch-to-batch variability on mechanical properties was found.
- the TZM showed a higher mechanical strength and a lower ductility compared to the Mo–5%Re; this result is not consistent with recent data.

In the light of these results, Mo alloys appear as a hard-to-handle class of structural materials. Any component or structure fabricated with these refractory metals, even without notches or welds, cannot be considered as a flawless body. The anomalous failure mode we observed represents a signal of warning. A ‘simple’ deterministic method seems insufficient for a sound design; a linear elastic fracture mechanics approach should be more suitable.

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## References

[1] G. Filacchioni, E. Casagrande, U. De Angelis, G. De Santis, D. Ferrara, J. Nucl. Mater. 212–215 (1994) 1288.
[2] V.V. Rybin, D.L. Smith, J. Nucl. Mater. 191–194 (part A) (1992) 31.
[3] M. Pott, Mo alloys: neutron irradiation effects on mechanical properties and microstructure, Meeting on Divertor Structural Materials R&D, Rome, 1992.
[4] T. Kuroda, IAEA/ITER/DS/30, IAEA, Vienna, 1991.
[5] G.M. Kalinin, J. Nucl. Mater. 179–181 (1991) 1193.
[6] P.E. Bennet, G.M. Sinclair, J. Basic Eng. Ser. D 88 (2) (1966) 518.
[7] M. Scibetta, R. Chaouadi, J.L. Puzzolante, J. Nucl. Mater. 283–287 (2000) 455.