Reassessment of temperature increase and equivalent strain calculation during high-pressure torsion

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Abstract. The problems of temperature increase during high-pressure straining and equivalent strain calculation are reassessed on the basis of general considerations and experimental evidence. Temperature evolution is measured for some pure fcc and hcp metals (Cu, Al, Ni, Ti and Zr) and different regimes of HPT (pressure, strain accumulated and strain rate). The results obtained are compared with modelling and theoretical estimates. A simple model taking into account microstructure evolution during HPT is applied in order to explain the consequent “straining-hardening-softening”. The heat release of plastic work is calculated on the basis of both the von Mises and Hencky equivalent strains giving some assessment on the applicability of these equations.

1. Introduction
Severe plastic deformation (SPD) is widely recognized as an effective process for grain refinement in metallic alloys [1]. Among numerous SPD processes are two most frequently used, namely, equal-channel angular pressing (ECAP) [2] and high-pressure torsion (HPT) [3] for processing bulk nanostructured materials. Initially, it was believed that SPD processes occur at ambient temperature, which corresponds to a low homologous temperature, typically, T < 0.3T_M, for metallic materials such as Cu, Ni, Ti, Zr. The introduction of dislocations that evolve into highly refined grain structures will lead to a progressive increase in flow stress and a corresponding increase in the rate of energy dissipation for SPD processing at a constant strain rate. At low deformation rates, approximately isothermal conditions may prevail in the HPT disks as anvils have good heat sink capability and the initial temperature would not increase significantly. However, an increase of temperature during SPD processing was detected for several metals. Yamaguchi et al. [4] used thermocouples embedded in billets and measured temperature increases of 25-30° during an ECAP pass on initially annealed pure aluminum. Zhilyaev et al. [5] inferred a temperature rise of ~140° during HPT of an as-cast Na-modified Al-7 wt% Si alloy based on changes in precipitate distributions. Finally, Todaka et al. [6] used a thermocouple embedded in the upper anvil of an HPT apparatus to measure temperature changes from 20 to ~45 ° at a location ~1 mm above the upper surface of high-purity aluminum samples. Aluminum, copper, iron and molybdenum were later selected as model materials [7]. The temperature increases at the early stages of straining but saturates to steady-state levels at
large strains. The increase of temperature of ~5° for aluminum, of ~15° for copper and of ~25° for iron (all metals were processed at $P=2$ GPa, 1 rpm) were detected and it was established the temperature rise was proportional to the hardness and rotation speed. Experiments and finite element modelling were used later [8] to estimate the temperature rise during high-pressure torsion. The results show the temperature rise is dependent upon the material strength, the rotation rate, the sample radius, the heat capacity and the geometrical dimension of the anvils. Nevertheless, there are no measurements on temperature rise in hcp metals. The present paper is designed to fill this gap and temperature evolution is measured for some pure fcc (Cu, Al, Ni) metals for comparison with the literature data and for some hcp metals (Zn, Ti and Zr).

![Figure 1](image1.png)

**Figure 1.** (a) Schematic of anvils for HPT processing and control temperature; (a) thermocouple is suited ~10 mm from the disk; (b) unit for temperature reading; (c) Al disk with hole punched.

Another significant issue of the SPD processing is how to compare the refined structure and the corresponding accumulated equivalent strain during ECAP and HPT (where other SPD processes shall also be included). There are two main approaches to calculate the strain using either the von Mises equation where $\varepsilon_{eq} = \sqrt[3]{\gamma}$ or by calculating using the Hencky strain where $\varepsilon_{eq} = \left(\frac{2}{\sqrt[3]{3}}\right)\ln\left(\sqrt{1 + \frac{\gamma}{4} + \frac{\gamma}{2}}\right)$, where $\gamma = 2\pi r N / h$ is calculated from the geometry of HPT deformation [3]. There was a quite long discussion in the literature [9-13] where arguments were given to one or other equation as being valid for calculations of the equivalent strain for SPD processing. A comprehensive explanation on the calculation of equivalent strain is given by Stuwe [14]. This issue is also addressed in this report and a possible correlation with the temperature rise during SPD processing is discussed.

2. Experimental material and procedures

Three fcc (Al, Cu, Ni) and three hcp (Zn, Zr, Ti) metals were used as the starting materials. The materials were purchased from GoodFellow™ and they have typical chemical compositions. The HPT specimens were in the form of disks having diameters of ≤10 mm and thicknesses of ≤1 mm. These disks were processed at room temperature by HPT for a total of $N = 10$ turns under applied pressures of $P = 1, 3$ or 6 GPa under dry sliding without any lubricant. The processing was conducted under quasi-constrained conditions with recordings of temperature every 15 seconds using a thermocouple embedded into the upper anvil as shown in Fig. 1(a). The temperature was displayed on the control unit in Fig. 1(b). In order to check on the influence of
the lubricant on the temperature rise, the nickel disks were processed under two conditions: under dry sliding conditions and with a MoS$_2$ oil lubricant (Moly Assembly Oil 150 produced by Sumico Lubricant Co. Ltd.). To investigate the influence of friction on the flash area, defined as the area around the cavity of 12.5 mm in diameter, two aluminum samples were cut: (i) a disk of ~12.5 mm in diameter and 0.35 mm in thickness and (ii) a similar disk but cut with a hole of 8 mm in diameter punched in the center as shown in Fig. 1(c). These Al specimens were processed under the same conditions as regular Al disks. All other details of the processing were very similar to those reported elsewhere [7].

3. Experimental results

3.1 Temperature rise during HPT processing of fcc and hcp metals

The relative increase of temperature in three fcc metals (Ni, Cu and Al) processed at different loads as a function of time (in minutes) or numbers of turns is shown in Fig. 2(a). The relative temperature increase recorded by thermocouple reaches values of ~35° for nickel, ~20° for copper and ~7° for aluminum after 10 whole revolutions. The values for copper and aluminum are slightly higher than reported elsewhere [7] where ΔT~15° for copper and ΔT~5° for aluminum were detected. Fig. 2(b) depicts the temperature rise during HPT processing of hcp specimens (Zr, Ti and Zn). Both titanium and zirconium show similar temperature gains of ~25° during HPT straining for 10 whole turns whereas plastic straining of the softer zinc heats the anvils only to ~5°. Fig. 3(a) shows a dependence of temperature rise on applied load for copper subjected to HPT at $P = 3$ and 6 GPa. There is a significant drop in temperature as the load pressure decreases from 6 to 3 GPa. Fig. 3(b) shows a comparison of the relative increase of temperature for titanium subjected to HPT ($P = 6$ GPa, 1 rpm): the open symbols are data obtained in the current work and the solid symbols are adapted from the earlier report [8]. It is clearly evident that data acquired in two independent experiments are fit together perfectly. Also data for a lower rotation speed (0.2 rpm) [8] are presented in Fig. 3(b). Thus, decreasing the rotation speed decreases significantly the temperature rise recorded.

Figure 2. Temperature increase as a function of time (number of turns) for (a) fcc (Al, Cu, Ni) and (b) hcp (Zn, Ti, Zr) metals subjected to HPT. Processing conditions are shown in inset.
3.2 Influence of friction in flash zone

Fig. 4(a) depicts the relative increase of temperature for three aluminum samples: a regular one (designated in Fig. 4(a) as Al), a second one with a decreased thickness of ~0.4 mm and a larger diameter of ~12.5 mm (Al #1) and a third one which is the same as the second but with a hole of 8 mm in diameter punched in the center of the specimen. Sample #2 after HPT processing represents a disk of 0.63 mm in thickness with roughness on both surfaces indicating that strain deformation took place. It is apparent that material from the flash area was displaced inside the cavity and essentially filled it to produce a sample almost identical to the regular one. The same occurs with sample #2 with the hole except that the material was insufficient to fill the cavity completely and therefore there remained a hole of ~4 mm in diameter as shown in Fig. 4(b). This resembles a ring specimen with a thickness of 0.54 mm. The regular aluminum sample and sample #2 show identical temperature evolutions as depicted by the solid green and the open red squares. By contrast, the sample with the hole demonstrates a slower kinetics of temperature increase. If one calculates the surface area subjected to straining for three samples, the area of the regular sample and sample #1 is identical and equals $S_{\text{disk}} = \pi d^2/4$ but the area of the ring specimen is $S_{\text{ring}} = \pi (d^2 - d_0^2)/4$, where $d$ is a diameter of the disk.
(~10 mm) and \( d_0 \) is the diameter of the hole after processing (~4 mm). The ratio \( S_{\text{disk}}/S_{\text{ring}} \) = 1.2 is in proportion to the final temperature rise of sample #1 and #2, in which 6°/5° = 1.2. It is apparent that flash area does not play a significant role in the temperature increase during HPT straining. In order to prove this supposition, an additional experiment was performed. A nickel disk was strained under the same conditions as for dry sliding but a lubricant was placed in the flash area of the upper and lower anvils. Fig. 5 shows the temperature increase as a function of time / number of rotations for the two cases with and without a lubricant. It can be seen that the curves are identical and as a consequence it is concluded that the lubricant is not important for the temperature rise during HPT straining. This is in good agreement with recent FEM modelling [8].

![Figure 5. Influence of lubrication on temperature increase: HPT nickel, P = 6 GPa, N = 10, at 1 rpm: solid symbols correspond to HPT processing at dry sliding; open symbols are for applying MoS\(_2\) lubricant around the cavities of both the upper and lower anvils.](image)

4. Discussion

4.1 Heat generation and temperature rise

The appearance of the curves of temperature rise for fcc and hcp metals as in Fig. 2 resembles the temperature dependency on time (or the number of cycles) in wear experiments [for example, in 15, 16]. It is logical because the nature of wearing and severe plastic deformation is identical, namely shear deformation. In practice the heat dissipation in these processes is very similar: a small disk and huge anvils as heat sinks in SPD and a small pin (or ball) and a large enough sample of the testing material attached to a base plate. As is noted in Figs. 2-3, the experimental points are fitted with a curve and it has only a single fitted parameter, \( A \):

\[
\Delta T = \frac{2A}{\sqrt{3}} \ln \left( \sqrt{1 + \frac{N^2}{4}} + \frac{N}{2} \right) \tag{1}
\]

This equation resembles the Hencky strain relationship. Definitely, the parameter \( A \) will depend on the conditions of the HPT straining. Fig. 4(a) shows the dependence of the temperature rise for copper strained at two loads: 3 GPa and 6 GPa. The parameter \( A \) is equal to \( A_6 = 6.9 \) (with residual of 0.996) for \( P = 6 \) GPa and \( A_3 = 2.99 \) (with residual of 0.934) for \( P = 3 \) GPa. It is apparent that the ratio \( A_6/A_3 = 2.3 \) is very close to the ratio of the loads.
4.2 Influence of the flash area

Unexpectedly from results obtained in these experiments (Figs. 5 and 6), there is no or only an insignificant influence of friction in the flash area on heat generation during HPT straining. This is supported by good agreement between the fraction of the surface areas subjected to HPT of the aluminum samples (Fig. 4) and the ratio of the maximum temperature reached after 10 turns. It is possible to estimate the maximum temperature that can be reached if 90% of the stored plastic energy is dissipated as heat. The mass of the two anvils is about \( m = 0.9 \text{ kg} \) and the heat capacity of the anvil materials is given elsewhere [7] and is equal to 460 J·kg\(^{-1}\)·K\(^{-1}\). An estimate will be conducted for three fcc (Al, Cu and Ni) and three hcp (Zn, Ti, Zr) metals. The fundamental material parameters are given in Table 1. The heat release during plastic deformation can be calculated on the basis of the well-known equation:

\[
q = 0.9 \cdot \sigma \cdot \varepsilon,
\]

where \( \sigma \) is the strength of the material and \( \varepsilon \) is the accumulated strain. The strength of materials can be estimated as \( \sigma \sim H_v/3 \) or \( \tau \sim H_v/3\sqrt{3} \). There are two different approaches for estimating the accumulated strain. The first is based on the von Mises equation for equivalent strain which is widely used in the SPD literature and the second is based on the Hencky equation which is sometimes reported to be invalid. The shear strain calculated on the basis of the HPT process geometry and averaged over the radius of the disk is \( \gamma = 0.5 \cdot 2\pi r N/h \), where \( r = 5 \text{ mm} \) is a radius and \( h = 1 \text{ mm} \) is the thickness of the HPT disk. The calculation gives the average shear strain, \( \gamma = 50\cdot \pi \). Then the maximum temperature rise can be calculated as

\[
\Delta T_{\max} = \frac{0.3 H_v \cdot \varepsilon_{eq_vM}}{m \cdot c_p},
\]

(3)

where \( \varepsilon_{eq} \) is von Mises (\( \varepsilon_{eq_vM} \)) or Hencky (\( \varepsilon_{eq_H} \)) equivalent strain, \( m \) is the mass of both anvils. Using the shear strength, \( \tau \), and the accumulated shear strain, \( \gamma \), the maximum temperature rise can also be estimated as \( \Delta T_{\max} = 0.15 \cdot H_v \cdot \gamma / (m \cdot c_p) \). The results of these calculations are summarized in Table 1. It can be seen that the estimation by applying the von Mises equation or applying shear strength and shear strain gives the values of the maximum temperature of the anvils which is in quite good agreement with the experimental data. However, an estimate using the Hencky strain leads to a value which is about one order of magnitude lower than experimentally observed. It should be noted that these values can change considerably if heat dissipation from the anvils to the surrounding environment is taken into account. Nevertheless, this estimate and the experimental data on the temperature rise tend to support the validity of using the von Mises equation for a calculation of the equivalent strain.

Table 1. Material parameters [17, 18, 19] and temperature rise estimated.

| Parameters \| Materials | Al  | Cu  | Ni  | Zn  | Ti  | Zr  |
|-------------|----------|-----|-----|-----|-----|-----|-----|
| Microhardness, Hv, GPa | 0.75 | 1.71 | 3.09 | 0.43 | 2.6 | 2.5 |
| Strength, \( \sim H_v/3 \), GPa | 0.25 | 0.57 | 1.03 | 0.14 | 0.87 | 0.83 |
| \( \Delta T_{\max} \), ° (Experimental) | 5 | 20 | 35 | 5 | 24 | 25 |
| \( \Delta T_{\max} \), ° (Calculated using v. Mises strain) | 3.9 | 8.8 | 15.9 | 4.4 | 26.8 | 25.8 |
| \( \Delta T_{\max} \), ° (Calculated using Hencky strain) | 0.25 | 0.57 | 1.02 | 0.16 | 0.98 | 0.94 |
| \( \Delta T_{\max} \), ° (Calculated using shear strength and strain) | 3.4 | 7.6 | 13.8 | 3.8 | 23.2 | 22.3 |
5. Summary and conclusions

1. The maximum temperature rise in three fcc and hcp metals was measured for HPT processing. The data for fcc metals are in good agreement with available data in the literature.

2. The detected values for the maximum temperatures are insufficient to activate grain growth in order to lead to a saturation in grain refinement and microhardness.

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