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Surface sliding revealed by *operando* monitoring of high-pressure torsion by acoustic emission

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ABSTRACT

High-pressure torsion (HPT) is widely used as a key method for microstructure control through deformation processing across a broad range of materials. However, certain gaps in process control impact its efficacy. In this study, we investigate the acoustic emission (AE) signals generated during HPT by considering commercially pure molybdenum as an example. By employing the adaptive sequential *k*-means algorithm, we analyse the AE stream to categorise and identify its sources. By comparing the kinetics of AE signal evolution during HPT processing at pressures of 2 GPa and 5 GPa, two distinct signal types are identified: one linked to plastic deformation and the other to workpiece slippage over HPT anvil surfaces. This research demonstrates the potential of AE tools for *operando* monitoring of HPT stability and detection of workpiece slippage, thereby enhancing the processing efficiency.

1. Introduction

High-pressure torsion (HPT) is one of the most established and popular methods of severe plastic deformation (SPD) for producing ultrafine-grained structures in diverse materials [1] as well as creating novel metastable materials and nanocomposites [2]. This process involves compressing a penny-shaped workpiece between two anvils that are twisted relative to each other.

A crucial aspect of HPT processing is the gripping of a workpiece by the anvils transmitting a torque through contact surfaces. Failure to achieve this regime may result in slippage, diminishing accumulated strain and potentially halting the process. Therefore, investigation of slippage under HPT has garnered significant attention, cf. [3]. Its effects were studied for various materials, e.g. Al, Cu, and Fe [4]. Slippage was also incorporated in the analysis of HPT of Ti [5]; its impact on pressure and accumulated strain was studied in [6], and its connection with non-shear flow was discovered in [7].

Recent studies detected slippage in HPT through marking [4] or sectioning [8] of a workpiece before processing. However, real-time monitoring of slippage remains challenging [9], and it appears imperative to address the critical issue of workpiece slippage *in operando* [10]. It is the primary objective of this study to devise, analyse, and validate an experimental approach to *operando* monitoring of HPT. To that end, we propose acoustic emission (AE) in the *operando* mode as a suitable experimental tool – to our knowledge, the first such application of AE. The AE method has been gaining popularity in the studies of plastic deformation [11–13] and of contact friction and wear [14]. The AE technique is selected for its capability of separating signals from different sources and monitoring their evolution over time individually. We employ an adaptive sequential *k*-means (ASK) algorithm [11] to discriminate between the AE signals stemming from workpiece deformation and from surface slippage, thus gaining insights into the evolution of these interrelated processes during HPT.

2. Experimental

Commercial-purity molybdenum (99.8 %) was used as a representative model material for HPT processing. Workpieces 13 mm in diameter and 1 mm in thickness were cut from round bars. HPT processing was carried out at ambient temperature using a specialised toolset (W.

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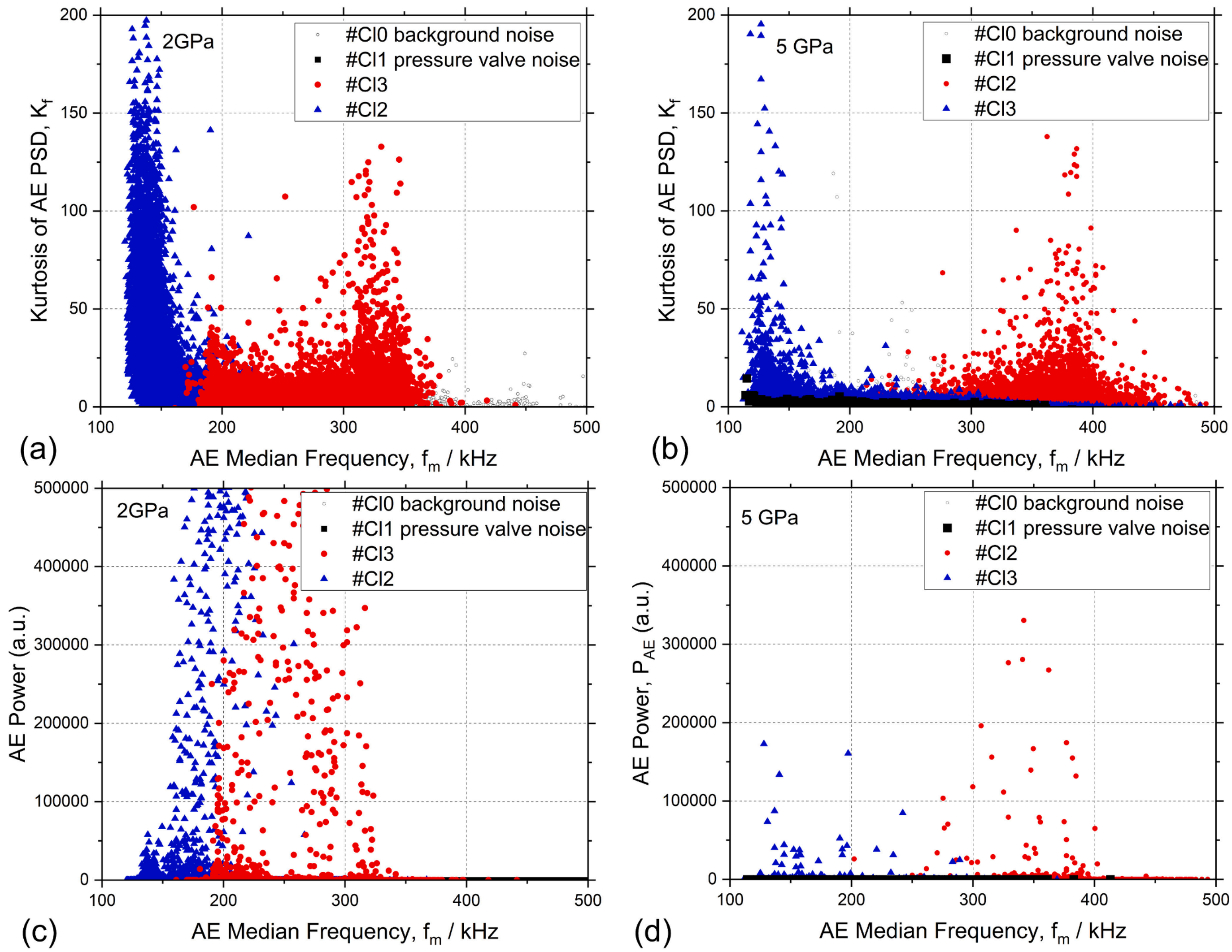

Fig. 1. Dependence of kurtosis of AE PSD (a,b,) and power (c,d) on AE spectral median frequency for HPT pressures of 2 GPa (a,c) and 5 GPa (b,d).

Klement GmbH, Lang, Austria) with quasi-constrained anvils having an impression diameter of 13 mm and a depth of 0.3 mm. The tool was operated at an angular velocity of 1 rpm for five anvil revolutions at controlled pressures of 2 GPa and 5 GPa. Both the pressure (force) and the torque were continuously measured and synchronised with the AE data.

The AE signal was acquired throughout the HPT processing in an *operando* regime using a Vallen AMSY-6 system with an AE3N 34 dB preamplifier and a VS370-A1 broadband sensor. The sensor was placed on the flat section of the upper side of the HPT anvil. AE was recorded as a continuous waveform stream. The ASK algorithm [11] was then used for the AE feature extraction, unsupervised data clustering, and analysis.

3. Results

A summary of AE spectral clustering is depicted in Fig. 1 illustrating the power and the kurtosis of the power spectral density (PSD) against the median frequency. Note that the number of clusters derived by the ASK algorithm is data-driven and is not defined *a priori*. Rather, ASK autonomously detects four significant clusters distinguished by the shape of their PSDs.

Cluster Cl0 was the only one identified in the signal recorded prior to the initiation of HPT processing. Its spectral density and time-history are virtually unaffected by the following HPT processing, while the increase of axial pressure significantly influences the behaviour of clusters Cl1, Cl2 and Cl3. This is evident in Fig. 2a and b that show the dependence of the accumulated number of cluster members on processing time for 2 GPa and 5 GPa, respectively. Comparing cluster growth kinetics with HPT processing progression allows monitoring of the dominant process mechanisms. Cl0 (noise) rapidly grows for both pressure levels throughout the entire HPT processing time. Cl1 experiences rapid growth initially, saturating over time and occasionally increasing again, Fig. 2c, d. A juxtaposition of the behaviour of Cl1 with HPT processing pressure and torque, normalised by their respective maximum values, unequivocally attributes this cluster to fluctuations in axial pressure generated by hydraulic cylinders in the HPT toolset. Hence, Cl0 and Cl1 are undeniably identified as ambient and instrumental 'noise', while Cl2 and Cl3 are associated with information-bearing signals. While Cl2 centres in the higher-frequency domain, its Cl3 counterpart is primarily composed of lower-frequency members. The data from the 2 GPa experiment exhibits a larger number of Cl3 members, whereas that from 5 GPa has more Cl2 members. The cluster size correlates with the source activity, which evolves over time.

In Fig. 2b, both Cl2 and Cl3 clusters of interest show steady growth after about 30 s at 5 GPa pressure. Cl2 grows rapidly with minor fluctuations, while Cl3 increases more gradually, reaching a lower saturation level after ~ 200 s. At 2 GPa, Fig. 2a, both clusters start growing similarly but exhibit distinctly different temporal evolution. Notably, Cl2 experiences intervals of very low or no growth and does not reach the same total as at 5 GPa. Cl3 grows slowly for ~ 50 s, then accelerates,

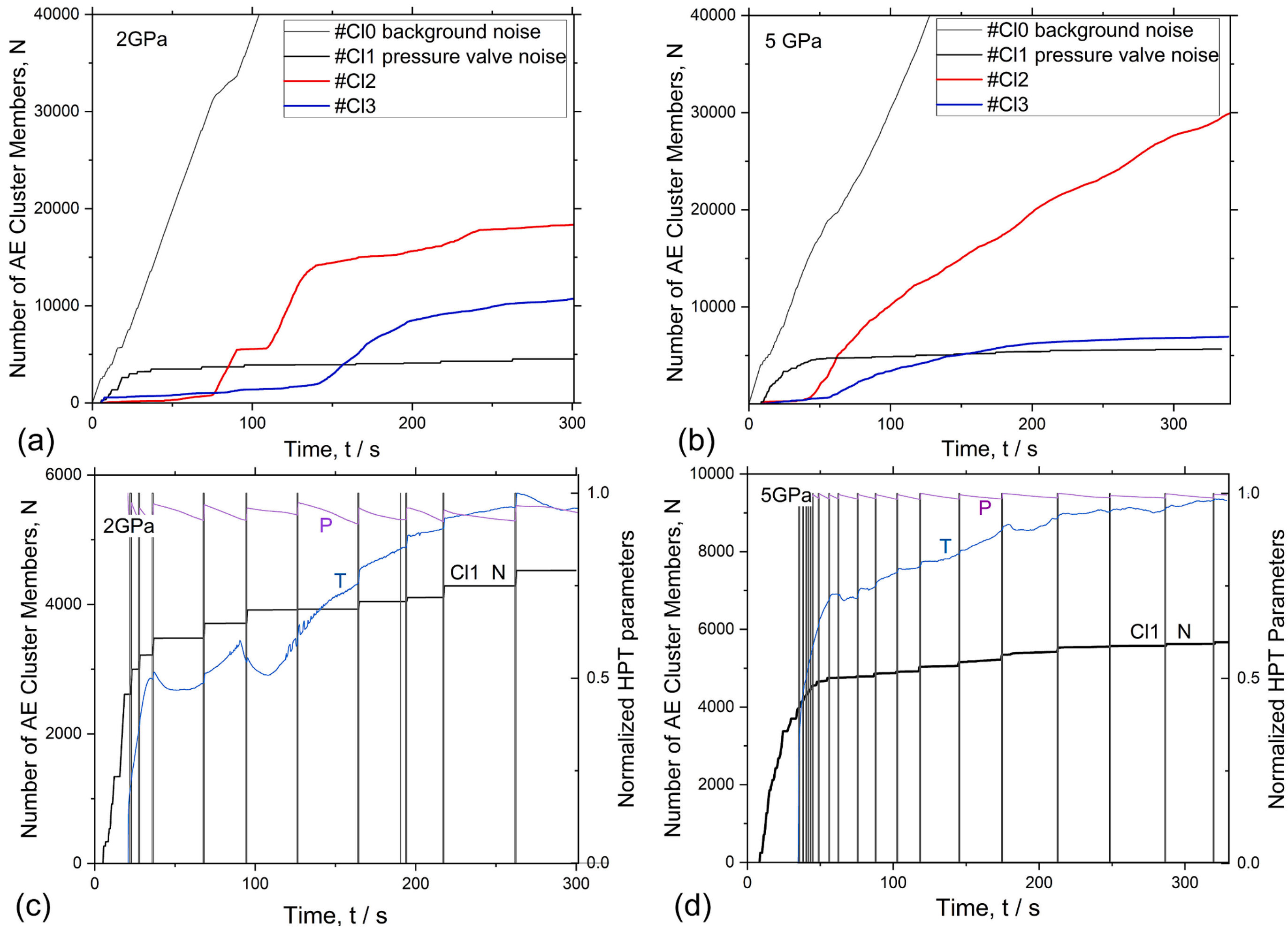

Fig. 2. Diagrams showing the evolution of the number of AE cluster members with time for the identified four significant clusters (a,b); Cl1 synchronised with HPT processing pressure (P) and torque (T) normalised by their respective maximum values; (c,d) for HPT pressures of 2 GPa (a,c) and 5 GPa (b,d).

saturating after 100 s. The total number of members is approximately half that of Cl2 but nearly double that of Cl3 at 5 GPa.

4. Discussion

The origin of AE in clusters Cl2 and Cl3 can be unravelled by analysing the evolution of the AE power, as suggested in [7], where three possible HPT regimes were identified as:

(i) shear flow when the material deforms plastically without slippage;
(ii) non-shear flow when the material still deforms plastically along with some slippage;
(iii) non-plastic regime when the workpiece exhibits slipping over the entire anvil surface.

With the increase in axial pressure, regime (iii) shifts towards (i), while in regime (ii) the process is unstable and may transit to (i) or (iii), depending on the material, pressure magnitude and surface friction. As mentioned above, Cl2 at 2 GPa, Fig. 2a, evolves exhibiting sporadic time intervals with very low or virtually zero plastic strain accumulation. These indicate interruptions or very low intensity of AE source activity. Such intervals are absent in the evolution of a similar cluster at 5 GPa, Fig. 2b. The entirety of the data suggest that cluster Cl2 can be attributed to the plastic deformation of the material, losing intensity or even vanishing due to workpiece slippage at low pressure; this corresponds to the transition from regime (ii) to (iii). By contrast, plastic strain, and the number of members in the corresponding cluster, increase proportionally to the anvil rotation angle, i.e., the time, in regime (i) when the pressure is sufficiently high to eliminate slippage.

Thus, it can be suggested that cluster Cl3 corresponds to the slippage of a workpiece on anvil surfaces since the source of AE signal reduces the rate of arrival of cluster members at the higher pressure, Fig. 2b. This corresponds to a gradual reduction of slippage and the transition from regime (ii) to (i).

Further confirmation of the proposed association of clusters Cl2 and Cl3 can be found in the evolution of torque in Fig. 2c, which clearly shows the intervals of torque reduction in response to strain rate drops caused by slippage. AE signals corresponding to Cl2 and Cl3 are rendered distinct by their PSD, resulting in vastly different distributions of frequency-dependent parameters, Fig. 1, whose behaviour is consistent with that reported earlier for plastic deformation [11,12] and dry friction [14]. At this stage, it would be premature to delve deeper into correlating the characteristics of the revealed clusters with specific mechanisms of plastic deformation.

5. Conclusions

This study has achieved its primary objective of establishing conceptual evidence that supports the viability of acoustic emission measurements for real-time detection of slippage during HPT. This has been demonstrated through the implementation of the advanced clustering methods applied to the AE datasets. This study paves the way for use of acoustic emission in the *operando* monitoring of slippage during materials processing by a broader range of SPD techniques beyond HPT.

CRediT authorship contribution statement

Y. Beygelzimer: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **D. Orlov:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **B. Baretzky:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **Y. Estrin:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **A. Vinogradov:** Writing – review & editing, Writing – original draft, Software, Investigation, Conceptualization. **R. Kulagin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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