Some Unresolved Problems of High-Pressure Torsion

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This overview highlights some salient features of one of the most popular severe plastic deformation techniques: high-pressure torsion (HPT). It focuses on the unresolved challenging problems of HPT. The problems selected touch upon some fundamental questions of mechanics of plasticity, fracture, and friction that are at the core of the HPT process. The scientific significance of these problems and the proposed pathways to resolving them are discussed. The article is meant to promote the use of HPT as a potent tool for studying plasticity at large strains theoretically and also as a practical method enabling novel micromanufacturing routes.

Keywords: *high-pressure torsion, slipping, equivalent strain, perfect plasticity, bonding*

1. Introduction

The idea of studying the behaviour of materials under high pressure goes back to P. Bridgman, who created an experimental rig suitable for such studies.[1)] The idea turned out to be fruitful and its further development gave rise to the modern-day technique of High-Pressure Torsion (HPT). It can be regarded as a progenitor of the currently popular research area of severe plastic deformation (SPD).[2)]

There exists abundant literature on HPT as one of the major methods of SPD. A comprehensive work of note is a review[3)] which presents the main principles of HPT and provides a detailed analysis of the effect of this process on structure and properties of metallic materials reported as of 2008. The history of HPT as a research area is to be found in an excellent review.[4)] The results of recent studies on the applications of HPT for producing advanced materials of different categories were surveyed in a number of publications. They refer to thermoelectric generators,[5)] magnetic materials,[6)] high entropy alloys,[7)] hydrogen storage materials,[8,9)] superconducting materials,[10)] semiconductors,[11)] and hybrid nanocrystalline alloys.[12)] Besides, review articles focusing on various aspects of HPT were published. The areas covered include texture evolution,[13)] solid state reactions,[14)] phase transformations,[15)] material behaviour at ultra-high strains (in excess of 1,000),[16,17)] finite element modelling,[18)] etc.

The present review differs from those referred to above in that it does not compile the known results. Rather, it outlines the unresolved challenging problems of HPT. Obviously, their selection reflects the predilections of the authors, and the list of the interesting problems is far from being exhaustive. It is hoped, however, that it is timely to draw the attention of the materials research community to these unresolved issues. They are related to some fundamental questions of mechanics of plasticity, fracture, and friction, and their resolution can be decidedly promoted by HPT. In addressing these issues, we shall try and cover the *Five Ws and How* in that an idea or concept, its originator, his or her provenance, the historical reference, the scientific context and significance, and the proposed means to resolve the issue will be elucidated. The key words relating to the posited problems serve as the titles of the sections of this article. At the beginning of each section, there is a graphical synopsis corresponding to its content (Fig. 1 Fig. 6).

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2. Gripping of the Sample by the Anvils

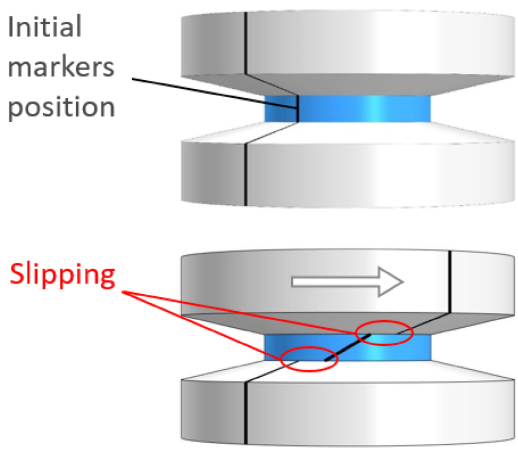

Fig. 1 Slipping during HPT.

This problem takes us back to the first publications of P. Bridgman,[1,19,20)] in which he describes seizure of a specimen by the anvils he refers to as pistons. Bridgman distinguishes between three stages of the process in relation to the normal pressure. In a scenario he outlines, the first stage is associated with low pressures when Coulomb friction between the specimen and the anvils takes place. The corresponding shear stress is smaller than the shear yield stress of the specimen material so that the specimen deforms elastically, while slipping on the rotating anvil surfaces. During the second stage, at a greater normal pressure, deviations from the Coulomb friction are observed. They are caused by collapse of part of micro-asperities on the rough specimen surface caused by their plastic deformation. At this stage, slippage of the specimen relative to the anvils still occurs and the shear stress is still below the shear yield threshold, but some zones of plastic deformation already emerge on the specimen surface. The second stage ceases when the normal pressure becomes so high that the entire specimen surface has seized and gets involved in plastic flow. Slippage does not occur any longer, and the shear stress reaches the level of the yield shear stress. That is when the third stage sets in and from now on the entire bulk of the specimen get engaged in plastic flow.

This picture is commonly accepted to the present day, although its proponent saw in it a serious scientific problem in need of being resolved.[20] The problem concerns seizure of the specimen by the anvils, which obstructs its slippage. Bridgman mentions an analogy with heavily loaded bearings in which seizing of contact surfaces occurs if lubrication fails. Such 'welding' of specimens to the anvils was observed by him also in torsion under pressure, especially with soft materials. The possibility of welding of some materials by friction was already known at the time, albeit for specially cleaned surfaces. This is distinctly different for torsion under pressure, in which process the specimens are usually covered with a strong native film containing adsorbed gases, moisture, and oxides, which tends to inhibit welding. Bridgman hypothesised that for sufficiently high pressures in conjunction with shear the protective film would fracture, the fragments getting embedded in a near-surface layer of the specimen, and seizure of the specimen by the anvils is facilitated. He cautioned that this matter requires a thorough investigation and outlined possible experiments to that end. However, his later publications do not mention such experiments.

In time that passed since the early publications,[1,19,20] there emerged new data which pose further questions relating to the hypothesis of the 'welding' of specimens to the anvils. Notably, research into cold welding showed that its practical realisation is possible only for a very limited range of metals and alloys.[21] This is confirmed by the experience with HPT, which shows that upon processing the specimens can be relatively easily detached from the anvils, which are made from contemporary high-strength materials. Furthermore, the studies on friction in metal forming processes show that native films provide efficient shielding of the specimen surface leading to a reduction of friction. This holds up to fairly high pressures, three- to fourfold of the yield strength of the material.[22] Unfortunately, no investigations at higher pressures were carried out. This is problematic in view of the importance of the seizure condition because slippage of an HPT specimen reduces the amount of plastic strain it can accumulate.[23–26]

To date, there is a serious deficit in the knowledge necessary to solve this problem. What is known can be condensed to the following statements: (i) the propensity for slippage increases with increased hardness of the material; (ii) for hard materials, such as iron and steels, slippage becomes more pronounced with growing angular velocity of the anvils;[23] (iii) the limit of the attainable effective strain rises with the axial pressure and the coefficient of friction;[23,26,27] and, finally, the experience shows that seizure of the specimen is improved if anvils have been treated by sanding.

According to the scenario described above,[1,19,20] seizure of the specimen by the anvils occurs when the friction shear stress τ_{fr} at their interface reaches the magnitude of the shear stress k of the deforming material:

$$\tau_{fr} = k \tag{1}$$

This relation expresses the seizure condition according to the currently accepted view of HPT. In modelling of this process this condition (or the sticking condition equivalent to it) is taken as the boundary condition at the contact surfaces of the specimen with the anvils, cf. e.g. Refs. 28 30).

Since the thickness of the specimen is much smaller than its diameter, it follows from eq. (1) in a first approximation that the shear in the bulk of the specimen produces a stress in a plane normal to the rotation axis which is equal to k. This is consistent with the notion that HPT represents simple shear under high hydrostatic pressure.

A more general concept[31] generalises this view of HPT in that non-shear flows are accounted for explicitly, 'on equal terms' with shear flow rather than being a small corrections to it. This approach enabled establishing a generalised condition of seizure (which was dubbed 'gripping') which holds for $\tau_{fr} \leq k$. Equation (1) follows from the generalised gripping condition,

$$\begin{cases} (\sigma_{zz} - \sigma_{rr})^2 + 3\tau^2 = 3k^2 \\ \tau \leq mk \end{cases}, \tag{2}$$

as a special case. Here σ_{zz} and σ_{rr} are, respectively, the axial and radial components of the stress tensor, τ is the shear stress in a plane normal to the anvil rotation axis, and m is the coefficient of friction, $\tau_{fr} = mk$. Based on the gripping condition, eq. (2), a rational explanation of several HPT effects was given.[31]

It was shown in Ref. 31) that for $m < 1$ and a sufficiently high axial pressure the material deforms plastically while slipping on the anvil surfaces. Starting from a certain anvil rotation angle the material slips as a whole, while its plastic deformation comes to a halt. The higher the pressure and friction, the greater is the cumulative effective strain attained at this moment. Unlimited deformation of the material by HPT is possible only if the condition $m = 1$ holds, when $\tau = k$ follows from (2).

According to the generalised seizure/gripping condition, HPT admits a certain plastic deformation of the specimen without gripping. This suggests a hypothesis regarding the mechanism ensuring the fulfilment of eq. (1) without the assumption of 'welding' of the contact surfaces. The quiddity of this hypothesis is that the native protective film on the specimen surface, which diminishes friction, transforms by deformation to a 'crust' which enhances friction, the friction stress rising to levels exceeding k. Phenomena causing such a transformation may include fracturing of the film due to non-shear flow, as well as mixing of the film material with the specimen material in a sub-surface layer due to shear. The latter process is akin to mixing of layers of materials with different stiffness by shear under pressure.[32] As a result of these processes a thin ‘crust’ of a stronger material than the specimen material itself may form. The friction stress of the film on the anvil surfaces will exceed the plastic flow stress of the material under shear so that the condition $\tau = k$ will be fulfilled.

Should this hypothesis sustain validation by experiment, known models of friction will have to be re-considered. Indeed, a corollary would be renewed increase of the coefficient of friction m a behaviour that has never been reported to date.[22] The possible connection between the problem of gripping during HPT and fundamental questions of friction and wear suggested by the above hypothesis is exciting. Verification of this hypothesis is therefore a hot issue warranting a serious experimental effort. Should its veracity be proven, it would become possible to use HPT as a suitable method for experimental investigation of the friction and wear phenomena in extremal conditions.

3. Equivalent Strain

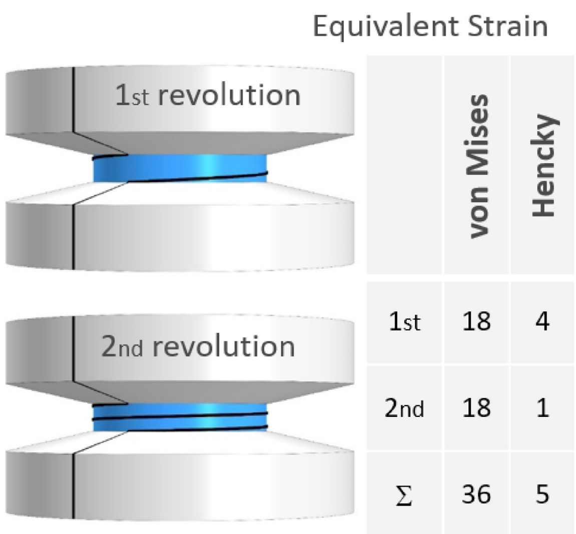

Fig. 2 Equivalent strain in HPT according to the von Mises and the Hencky definitions.

For every metal forming process, there is a simple formula for estimating the equivalent strain involved.[33] In this regard, HPT is quite fortunate, as there are two such formulae for the HPT process. They give drastically different results, however. Obviously, we have a serious problem, which is deeply rooted in the foundations of solid mechanics.

Both formulae for the equivalent strain were obtained under the assumption of laminar flow of matter along circular paths. In a cylindrical coordinate system, the velocity field for such motion is determined by the following relations:

$$v_\varphi = \frac{\omega r z}{h}, \quad v_r = v_z = 0, \tag{3}$$

where r, φ, and z are the coordinates of the cylindrical system, the z axis coincides with the symmetry axis of the anvils, ω is the angular velocity of the upper anvil rotation, the lower anvil being considered stationary, and h is the specimen thickness.

The velocity field (3) describes simple shear, under which the layers of matter parallel to the specimen surface slip relative to each other.[34] The corresponding shear rate $\dot{\gamma}$ and shear strain γ are determined by the following relation:

$$\dot{\gamma} = \frac{\partial v_\varphi}{\partial z} = \frac{\omega r}{h}, \tag{4}$$

$$\gamma = \int \dot{\gamma} dt = \frac{\varphi r}{h}, \tag{5}$$

where t is time and φ the anvil rotation angle.

As mentioned above, two equations for the effective, or equivalent, strain associated with simple shear are in circulation:

$$e_M = \frac{\gamma}{\sqrt{3}}, \tag{6}$$

$$e_H = \frac{2}{\sqrt{3}} ln\left[\left(1 + \frac{\gamma^2}{4}\right)^{1/2} + \frac{\gamma}{2}\right]. \tag{7}$$

Here e_M and e_H denote, respectively, the von Mises and the Hencky equivalent strain.

For <1, eqs. (6) and (7) yield similar values for the equivalent strain. However, for large shear strains characteristic of HPT deformation the values of e_M and e_H may differ by orders of magnitude. Which one of the two equations is correct? Disputes between the supporters of these two equations based on arguments of various kinds have been around for many years.

A phenomenological argument in favour of e_H as a measure of equivalent strain, is based on the so called ‘unified curve’ hypothesis. It posits that for metals deforming at low homologous temperatures the same equivalent strain should give rise to the same level of strain hardening.[35] From this standpoint, the von Mises equivalent strain e_M for finite shear strains turns out to be ‘unreasonably high’, since the corresponding strain hardening of a metal is much smaller than for the same equivalent strain of elongation.

In Fig. 2, the magnitude of the respective strain measures of equivalent strain accumulated by the material over the first and the second anvil revolutions are shown. The calculations show that the von Mises strain acquired over each of the two revolutions considered is the same, while the Hencky strain accumulated over the second revolution is just a quarter of that accumulated over the first revolution. The calculations of the strains were carried out at a point $r = 5$ mm away from the specimen axis for the specimen thickness of $h = 1$ mm.

The various pros and cons in relation to e_M and e_H based on the principles of solid state mechanics can be found in Refs. 36 48). Thus, the authors of Refs. 36 39) justify eq. (6) by energy considerations. By contrast, in Refs. 40, 41) it was argued that for large γ eq. (7) must be used, as dictated by the need to exclude rotations from the strain gradient in a consistent way.

In Ref. 49), the equivalent strain is considered as the governing variable in the deformation process. Using the reasoning based on the group properties of geometric transformations[50] in conjunction with the additivity principle, it was shown that the equivalent strain for simple shear must be a linear function of γ. A corollary is that eq. (6) applies, thus ruling out the validity of eq. (7).

The core idea of the article[49] is that the equivalent strain accumulated by the material between two deformation states must be an objective quantity. In the context of HPT this means that the equivalent strain acquired by the material upon the rotation from the angle φ_1 to the angle φ_2 depends on the difference $(\varphi_2 - \varphi_1)$, rather than on these angles themselves. Otherwise, due to the symmetry of the process, it would not be possible to determine the angle φ_1 objectively. Indeed, the equivalent strain cannot depend on somebody's tinkering with the anvils. This property can be ensured only if the equivalent strain is a linear function of the rotation angle. This is tantamount to the validity of eq. (6). Equation (7) which is non-linear in the rotation angle does not satisfy the objectivity requirement.

Obviously, we are facing a serious problem with calculating the equivalent strain for simple shear even with this approximate model of HPT not to speak anpit more realistic estimates this paramount characteristic of the process. It was for good reason that P. Bridgman wrote: "The actual distribution of stress and strain in the disk is evidently very complicated and must differ greatly from the mean values just discussed".[1] Recent research supports this statement.[51–55]

The challenging problem of calculating the equivalent strain under simple shear or HPT is directly related to the question of the influence of rotations on the properties of a material. According to the principle of material-frame independence,[56] a rigid rotation does not affect the properties. Hence, rigid rotations must be excluded from the calculation of the equivalent strain, as done, e.g. in Refs. 40, 41). On the other hand, the microstructures and the properties of materials processed in simple shear deformation mode are substantially different from those subjected to pure shear deformation, which differs from the former in that it involves no rotation. This is confirmed convincingly by numerous investigations of severe plastic deformation,[57] some of which including specially designed experiments on simple shear.[58–60] Possibly the controversy could be resolved by assuming that under simple shear the rotation is not rigid and occurs within a representative material volume.[61,62] For that reason, it would not be subject to the mentioned postulate of solid mechanics and could thus have an influence on the material properties.

The ongoing debates about the equivalent strain in HPT indicate that research into the effect of pure shear and simple shear on materials are not only of practical, but also of fundamental interest.

4. Perfect Plasticity

In the 60s 70s of the 19th century, the French mechanical engineer Henri Édouard Trescá has observed a phenomenon that was later dubbed perfect (or ideal) plasticity. Based on the results of a large number of experiments involving various solids (including lead, tin, copper, iron, clay, paraffin wax, ice, etc.) Trescá has come to the following conclusions which we cite from his book:[63]

1) at sufficiently high pressure, solids can flow similarly to fluids; 2) there exists an intermediate range of plastic strengthening occurring after the elastic limit is reached, but before the onset of plastic flow; 3) there exists a material characteristic (the coefficient K) which represents the maximum shear stress at which regardless of the kind of test, the material flows.

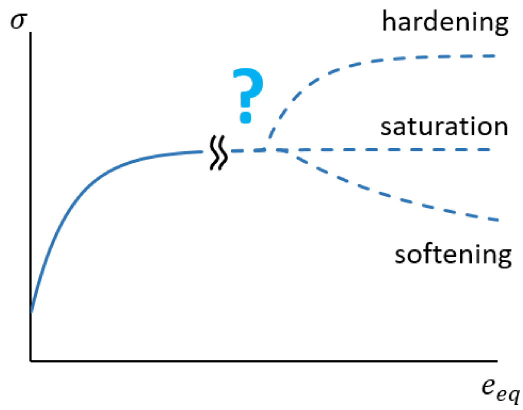

Fig. 3 Different types of behavior of the stress-strain curve at large strain. The curve labelled 'saturation' corresponds to perfect plasticity.

The methodology of Trescá's experiments was very appropriate considering the level of solid mechanics at the time. For instance, he punched cylindrical elements out of sheets using a hardened steel bar of a smaller diameter, or extruded cylindrical samples through round, triangular, or rectangular orifices or impressions in the sheet. Further tests included compression of cylindrical samples between hardened plates and backward extrusion of bulk cylinders of different height in the presence and the absence of lateral constraints. The outcomes of these tests provided a foundation for plasticity theory, especially in connection with perfect plasticity, which is based on the assumed constancy of the flow stress of materials.[64]

The hypothesis that after a large strain ideal plasticity sets in has been haunting the minds of researchers since Trescá's experiments. Among the first researchers who observed an anomalously weak strain hardening at large strains in torsion under high pressure was P. Bridgman.[65] Later studies confirmed that the deformation curves tend to saturation with increasing strain, cf. the review articles.[66–68] Arguably the most convincing evidence of perfect plasticity was uncovered in HPT studies.[69–72] Not only did these works demonstrate the constancy of the torque at large shear strains, but they also established that the microstructure of the deforming material remained unchanged in the process of straining.

At least two questions come to mind in connection with perfect plasticity: (i) What is the root cause of this phenomenon? and (ii) Does it occur in the simple shear mode only or is it also possible under other deformation modes?

These questions have not been entirely resolved yet. Bridgman believed that the anomalously low strain hardening rate he observed was a unique property of simple shear deformation. To substantiate this viewpoint, he suggested an idealised atomistic model of deformation of metals, which illustrated the principal difference between simple shear and tensile extension.[65] The author of Refs. 58 60) is also of the opinion that it is the loading mode that largely determines the ensuing microstructure and the properties of metals at large deformations.

By contrast, according to Ref. 69) the experimental results provide clear evidence that the microstructural evolution obeys universal principles established in Refs. 73, 74) regardless of the deformation mode. That is why the authors of these reports believe that at sufficiently large strains the perfect plasticity phenomenon must be common to all loading modes, even though they only observed it for HPT deformation. The authors of Refs. 70 72) concur with this viewpoint. In a recent paper, Gil Sevillano looked at the path dependence of strain hardening at large strains and concluded that, while the microstructure evolution and the associated strain hardening rate is path-dependent, the general trend to steady state tends to be universal.[75)]

Despite greater clarity that has been achieved in relation to perfect plasticity, the issue can still be considered to be open because of the relative smallness of strains associated with deformation modes other than simple shear. HPT enables access to strains that by far exceeds those attainable by other methods and is more suitable when it comes to studying the question of perfect plasticity.[76–79)] An extension of the experimental possibilities may be possible by combining different deformation schedules.[80,81)]

As indicated above,[75)] the characteristics of metals associated with perfect plasticity may depend on the pre-processing history (see also Ref. 80)). An interesting observation that deserves mentioning is that after a certain threshold in strain perfect plasticity may break down leaving the stage to renewed strain hardening of the deforming material.[16,17)] Again, it is not quite clear whether this resumption of strain hardening after a period of perfect plasticity without a change of the deformation path is universal or not.

It is fair to say that presently there is no consensus on the nature of perfect plasticity. In most publication on the matter, it is claimed that perfect plasticity can be explained in terms of dynamic equilibrium between grain fragmentation and dynamic recrystallisation. Grain boundary migration has a role to play in this scenario. Viewed in this way, the perfect plasticity phenomenon can occur for any deformation mode. Another possible scenario leading to ideal plasticity with progressing SPD-induced grain fragmentation was discussed in Ref. 82) where a critical grain size was found below which no dislocation storage, and hence no strain hardening, is possible. This critical grain size is inverse in a power of the strain rate and has a strong exponential dependence on temperature through the grain boundary diffusion coefficient. In this view, the occurrence of perfect plasticity for sufficiently small grain size does not depend on the deformation path leading to this level of grain refinement.

An alternative hypothesis was put forward in Ref. 83), where perfect plasticity is related to a percolation transition in a network of grain boundaries, which is exclusive to simple shear. The central idea is that at micro scale plastic deformation of metals is described by piecewise isometric transformations.[84)] The reasoning us as follows.

Under plastic deformation, the crystal lattice of a metal undergoes elastic strains which do not exceed 10 ^{3}. It follows that at the crystal lattice scale the deformation is describable as nearly isometric transformation under which the length of a segment remains practically unchanged. (It should be remembered that isometric transformations comprise transition, rotation, and symmetric reflection.)

According to the near-isometric transformation theorem,[85)] a continuous mapping isometric in a small vicinity of every point is isometric in the entire domain considered. Hence, to cause a finite change of a segment length, the transformation describing large deformations must belong to the class of isometric transformations with discontinuities, i.e. piecewise isometric transformations.

Indeed, large plastic strains in metals are furnished by discontinuities of isometric transformations, such as discontinuities in displacements, rotations, and symmetric reflections. Dislocations, disclinations, and twins are well-known examples of carriers of such discontinuities.[86)] The surfaces swept during the motion of such crystal lattice defects form sets of singularities of the isometric transformations.

It was also hypothesised in Ref. 83) that at large strains there is a further possible mechanism of isometry breaking. It is caused by percolation of shears on large-angle grain boundaries, which gives rise to perfect plasticity. The characteristic size of the isometric fragments decreases with strain if the growth of strain is accompanied with narrowing of its source. Unlike in any other deformation mode, this does not happen in simple shear, which enables a steady state deformation regime, i.e. perfect plasticity.

The occurrence of perfect plasticity at large strains signifies the qualitatively different state the material is in. Unravelling the mechanisms underlying perfect plasticity is of fundamental scientific interest. The situation is similar to that with other physical phenomena, such as superplasticity, superfluidity, and superconductivity, where it took decades to understand the key processes. The HPT method may become a decisive tool for solving the outstanding problems relating to perfect plasticity.

5. Solid State ‘Turbulence’

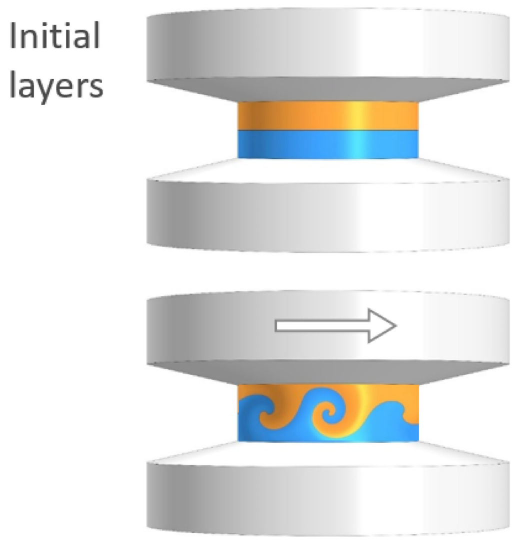

Fig. 4 ‘Turbulence’ during HPT.

Some ten years after Trescá’s observation of laminar plastic flow of solids, the English mechanician, physicist and engineer Osborne Reynolds discovered non-laminar (‘sinuous’ in his terminology) flow of fluids. In a first report on what later came to be known as ‘turbulence’, he demonstrated almost instantaneous spreading of a dye in a vigorous stream of water.[87] Reynolds’ hypothesis was that rapid transport of impurities is caused by random vortices, which carry an impurity particle in a relay-race manner, from one vortex to the next. Currently we know quite a lot about turbulence of gases and liquids, but to the present day the phenomenon of turbulence remains one of the most enigmatic riddles of Nature.[88]

HPT studies indicate that the time has come for researchers to pay serious attention to non-laminar flows of solids as well. It is known that at micro scale, the movement of a material deforming plastically is irregular and is characterised by a random velocity field. This chaotic motion never broke through to the macroscopic scale, however. Such metal forming processes as rolling, extrusion, wire drawing, stamping, etc. exhibited only laminar plastic flow of metals. However, in recent HPT investigations of metallic laminates structures were found that provide evidence to irregular, pulsing flow of solids at macro scale, cf., e.g. Refs. 12, 89 94). The observed features of plastic flow possess some characteristics of turbulence,[95] as in addition to its irregular character it changes the topology of metal layers and leads to their ruptures and mixing. We therefore refer to the observed phenomenon somewhat loosely as ‘solid-state turbulence’ (SST).[96]

The physical origin of SST is distinctly different to that of the turbulence in fluids. The latter sets in once the flux velocity exceeds some critical threshold value. By contrast, experiment shows that the velocity factor has no effect on SST. It’s early days with SST, and the phenomenon has hardly been studied in-depth. In most publications its occurrence is established, and material science effects are mentioned, but the underlying mechanisms are still not known. To our knowledge, there is a single publication,[89] where turbulisation of a shear flux in a multi-layer metallic laminate was observed in numerical experiments based on rheology of non-linear viscous fluid.

A hypothetical physical mechanism of SST was outlined and substantiated in a series of articles,[61,62,83,90,96–98] where this phenomenon is associated with the principal property of the solid state the long-range order, i.e. the ability of a solid body to retain its shape and to change it only if certain loads are applied.

At some stages of their emergence, the spatial patterns of SST resemble geological formations.[99] The evolution of the geometry of a laminate composed of alternating layers of hard and soft materials can be caused by loss of stability of the layers in the stress field generated by the shear of the laminate under pressure.[90,97] The random velocity field associated with such stress state leads to ruptures within the hard layers and their filling with the softer material under pressure. It is of great interest to look into the stirring and mixing of different solids induced by these processes.[100]

A mathematical description of the mixing-type motions, which are characteristic for SST, cannot be provided by the traditional continuum approach, which assumes smoothness of the velocity field.[101] In such a case, theoretical investigations are based on discretisation schemes, cf., e.g. Ref. 102) or generalised continuum models, cf., e.g. Ref. 103). One of the variants of the discretisation approach, which was successfully used in Refs. 96, 104) to model SST, is the ‘moveable automata’ technique, cf., e.g. Ref. 105).

Studying SST as a stochastic non-linear phenomenon is of significant scientific interest, especially in view of its occurrence not only in laboratory environment but also at the length scale of the Earth’s lithosphere. Potential practical outcomes are also promising, since SST opens avenues to solid-state mixing under pressure, with a great potential of the process in materials engineering.

6. Bonding

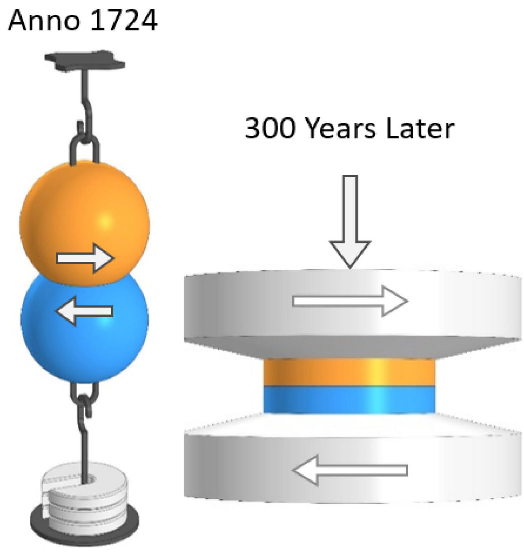

Fig. 5 Bonding by shear deformation under pressure.

Three hundred years ago, the British naturalist, clergy man, engineer and free mason John Theophilus Desaguliers, who was a Fellow of the Royal Society and assistant to Isaac Newton, demonstrated bonding of metals by torsion under pressure. In his experiments he put together two capped balls and compressed them while rotating the balls relative to each other. As a result, the balls bonded together, so that a rather substantial force was required to separate them.[106] This appears to have been the first demonstration that a strong bond between metallic bodies can be achieved.

Desaguliers’ experiments became part of the treasure chest of studies on friction and wear. They came to bearing more than two centuries later in investigations of seizure of metals during co-deformation.[107] The latter paved the way to the process known as cold welding (CW), which does not require extra heating by external heat sources.[108] It enables avoiding detrimental effects of heat on materials a feature that makes CW attractive to scientists and engineers and is used in mechanical engineering, electrical engineering, and electronics.[109]

The modern view on CW are based on the film theory, whose tenet is that for a strong bonding a tight contact between the two exposed metals is required.[109–113] The quiddity of CW is described in current models in the following way. In the initial state, the surfaces of metal blanks are covered with rough isolating films, such as hard and brittle surface layers originating from scratch-brushing, oxides, or other impurities. During co-deformation of the components to be joined, the contact area increases, which leads to fracturing of the isolating films and denuding of the metals. Under sufficiently high contact pressure, the exposed materials are extruded into the gaps formed, which brings them into intimate contact with one another, which leads to the formation of strong bonding.

In this conception, destruction of isolating films is governed solely by an increase in the contact area, i.e. by elongation strain in the tangential plane. This predicates the use for CW of such processes as stamping, rolling, extrusion, and wire drawing.[107,113]

It is our belief that HPT can add new colours to the palette of studies on CW, both fundamental and applied ones. This is suggested by recent investigations of solid state 'turbulence' (cf. Section 5), which showed that hard layers surrounded by softer ones lose stability when subjected to shear under pressure. The resulting vortex fluxes cause mixing that transforms a laminar structure to complex patterns found in the Earth's lithosphere, such as waves, folds, vortices, etc.[99] Considering isolating films as hard layers one concludes that shear in conjunction with high pressure will lead to the occurrence of such patterns in the weld zone. There is evidence that similar structures do emerge in explosive welding[114] and friction stir welding,[115] which enhances the strength of bonding by these methods.

The models of CW based on the film theory do not consider the possibility of shear deformation and the ensuing effects. They may influence the bonding process and deserve attention. One possible approach to studying bonding in connection with distortion of layers due to mixing-type motions is discretisation of a continuum, cf. Section 5. As an example, molecular dynamics was used to that end.[116] Alternatively, one can employ a phenomenological approach.

Such an approach was followed in studies of external friction and wear,[117–122] Specifically the zone of contact between two solids is considered as an independent entity the so called 'third body' (TB). It comprises the rough surfaces, thin near-surface layers engaged in the shear deformation, as well as films, lubricants, impurities, gases, and wear products residing on the surfaces and pores within the zone considered. In other words, this concept treats external friction at the interface between two solids as shear deformation of TB.

Assigning to the contact zone the properties of an independent body makes it to an interesting object of study to specialists in various disciplines and promotes interdisciplinary research.[117] This is of significance in the context of CW with shear, which, as mentioned above, may induce various physico-chemical transformations of matter in the contact zone.

Theoretical investigations of CW involve development of mathematical models capable of handling the formation of the structure and properties of the 'third body' during its plastic deformation under pressure. The existing models of TB devised to study friction and wear[118–122] can be used to analyse the friction force as a function of external factors, including pressure, sliding velocity, and temperature. Similar models for CW need to account for the formation of bonding between the mating metals and to provide a tool for calculating its strength under various conditions of loading of the weld. It is of paramount importance that the TB models enable solving coupled problems.[120] In the CW context this means accounting for the effect of mechanical properties of the deformation-induced bond on the plastic flow of the structure that created it.

The TB concept may have an interesting edge if it is to the entire sample, rather than the individual interfaces. Figuratively speaking, at sufficiently large strains mixing of the different constituents and their bonding by HPT turns the entire sample to a tortuous weld, thus creating a completely new material.[12,15,123–125] We can view it as a 'third body' born between two anvils. The problem consists in describing the evolution of the characteristics of the 'newborn' during HPT. As the main characteristic of the TB, the dependence of the torque (or the mean shear flow stress) on the anvil rotation angle (or the mean shear strain) can be considered. It will obviously depend on the magnitude of the axial pressure.

The TB generated by HPT occurs as a thin disk and is thus a planar object. It can be crushed to powder, which can then be used for obtaining bulk specimens by powder or additive manufacturing technologies. It should not be difficult to develop a phenomenological model of the new material thus produced, which considers all stages of the process, including HPT. It can be envisaged that materials synthesised in this way can be used in micromanufacturing leading to marketable new technologies.

7. HPT: Possible Applications

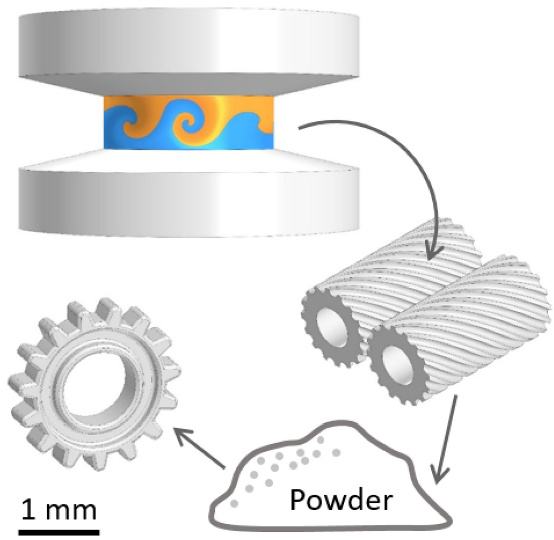

Fig. 6 Micromanufacturing from HPT-Powder.

In the foregoing sections we discussed several problems of fundamental nature relating to severe plastic deformation. Owing to a unique interplay between high pressure and sheer unlimited strain, HPT may provide decisive clues to their solution. This justifies the efforts at developing this process in laboratory environment. In addition, HPT clearly has the potential to become part of manufacturing processes.[17,126–129)]

However, despite burgeoning research activity in nanostructured and ultrafine-grained materials produced by SPD, it is fair to say that so far, the practical outcomes of research have not met the expectations of industry. The prevailing sentiment is that without upscaling of the SPD processes, commercialisation of laboratory-proven technologies would not be accepted by industry and enjoy commercialisation successes.[130)] In that article a timely account of what has been achieved, with a few examples of successful applications, and what is required for a broader implementation of SPD technologies in industry-scale manufacturing was given. The concerns about the possibilities of upscaling the process are particularly acute for HPT, which commonly produces small penny-shaped and -sized specimens. That is why in recent years significant efforts went into developing HPT equipment capable of processing bigger specimens[131–133)] or enabling a semi-continuous HPT processing referred to as high pressure torsion extrusion (HPTE).[134–136)]

While upscaling is still ‘the order of the day’ with most SPD processes, it was suggested that for HPT the opposite strategy, i.e. downscaling, would be a viable and promising route to commercial products.[137)] A specific proposal made was that of using HPT in microfabrication. Indeed, the extreme grain refinement enabled by HPT of miniaturised parts of MEMS, mini-drones, cogwheels for watches, etc. brings about a double benefit. First, HPT processing provides the material with the desired levels of strength owing to its ultrafine crystallinity. Second, the requirement for reproducibility and low scatter of the properties of a batch of manufactured articles can easily be satisfied, since the average grain size of an article is much smaller than its characteristic dimensions. (Averaging over many grains across the article eliminates the sensitivity of its mechanical properties to the occurrence of unfavourably oriented grains detrimental to the mechanical performance.) As the average grain size of the HPT-processed metallic materials is in the range of 0.1 1 µm, it is realistic to manufacture miniaturised articles with typical cross-sectional dimensions down to 10 µm. A great advantage of this downscaling concept is that manufacturing of a large number of such miniaturised articles becomes possible with the laboratory-scale HPT equipment, virtually as a desktop fabrication.[137)]

It should also be mentioned that as part of the microfabrication process HPT can be employed to completely modify the blanks and produce truly new materials with radically changed phase composition and inner architecture.[123,138,139)] Specifically, such SPD-induced material synthesis in the bulk of a blank can be furnished through material transport by HPT accompanied by stirring and mixing leading to solid-state reactions.

Combining HPT with powder processing and additive manufacturing technologies outlined in Section 6 represents a possible new pathway to producing novel materials.

We believe that the downscaling of HPT processing outlined above has great innovation reserves untapped into and expect that this research direction will provide guidelines to new microfabrication routes in the spirit Bridgman envisaged in his pioneering work.

8. Conclusion

A brief analysis of HPT-related problems demonstrates that despite its venerable age approaching 100 years, high-pressure torsion is young and agile. It provides a playground for various disciplines, including materials engineering, mechanics, physics, chemistry, geology, science of friction, etc., and is full of enigmas connecting the process with these scientific disciplines. Thus, HPT may play an important role in solving some mysteries of Nature. A rapid trend towards downscaling metal forming processes and development of the manufacturing industries for fabricating miniaturised articles heralds the approach of broad application of HPT and cognate technologies in industry. All that gives a strong motivation for further research into this process.

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