An overview on severe plastic deformation: research status, techniques classification, microstructure evolution and applications

E. Bagherpour[1], N. Pardis[1], M. Reihanian*[2], R. Ebrahimi[1]

1. Department of Materials Science and Engineering, School of Engineering, Shiraz University, Shiraz, Iran

2. Department of Materials Science and Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran

Abstract

The present overview gives a new approach toward developments and recent achievements in severe plastic deformation. The review focuses on several subjects. First, an outline of SPD research status in the world is presented by literature analysis based on the total number of publications, citations and the contribution of the top-ranked countries. Second, the mechanisms of grain refinement and grain growth during SPD processing are discussed by means of the latest concepts. Third, all SPD methods invented so far are classified based on a new approach. Up to now, the growing tendency of researchers to introduce new SPD techniques results in a large number of SPD methods which can be considered as new or modified techniques or a combination of previous ones. Such a reference can help to prevent the future duplication to introduce the SPD processes, which are technically similar. At the end, the practical applications of ultrafine/nanostructured materials and industrial commercialization of SPD methods are summarized.

Keywords: Severe plastic deformation; Nanostructured materials; Grain refinement; Research status; Application

*Corresponding author. m.reihanian@scu.ac.ir (M. Reihanian);

Tel.: +98 61 33330010 19x5684; fax: +98 61 33336642

List of abbreviations

ABE	Accumulative back extrusion
ACCB	Accumulative Channel-Die Compression Bonding
AccumEx	Accumulated Extrusion
AE	Alternate Extrusion
AFF	Accumulative Fold-Forging
AFSE	Axi-symmetric forward spiral extrusion
ARB	Accumulated roll bonding
ASB	Accumulative Spin Bonding
C2S2	Continuous Confined Strip Shearing
CAD	Channel Angular Deformation
CCB	Continuous Cyclic Bending
CCC	Cylinder Covered Compression
CCDF	Cyclic Closed-Die Forging
CEC	Cyclic Extrusion-Compression
CECAP	Cyclic Extrusion Compression Angular Pressing
CECRE	C Shape Equal Channel Reciprocating Extrusion
CEE	Cyclic Expansion-Extrusion
CFS	Cyclic Flaring and Sinking
CG	Coarse Grained
CGP	Constrained Groove Pressing
CP	Commercially Pure
CRB	Cyclic Rotating Bending
CR-ECA	Integrated conventional Tandem rolling with ECA deformation
CSCW	Clustered-Small-Cell Wall
CTE	Compound Twist Extrusion
CVCDE	Variable Cross-Section Direct Extrusion
CVCE	Continuous Variable Cross-Section Recycled Extrusion
DECLE	Dual Equal Channel Lateral Extrusion
DDW	Dense-Dislocation Wall

DTZ	Dislocation Tangle Zone
EBSD	Electron Back Scatter Diffraction
ECAD	Equal Channel Angular Drawing
ECAP	Equal Channel Angular Pressing
ECAP-FE	Equal Channel Angular Pressing-Forward Extrusion
ECATD	Equal Channel Angular Torsion Drawing
ECFE	Equal Channel Forward Extrusion
ECSEE	Elliptical Cross-Section Spiral Equal-Channel Extrusion
EL	Laminar Structure
FE-ECAP	Forward Extrusion- Equal Channel Angular Pressing
FSP	Friction Stir Processing
FSBE	Friction Stir Back Extrusion
GNB	Geometrically Necessary Boundary
HAGB	High Angle Grain Boundary
HCAE	Half Channel Angular Extrusion
HPDT	High-Pressure Double Torsion
HPT	High Pressure Torsion
HPT-CS	High pressure torsion-cylindrical segment
HPTT	High Pressure Tube Twisting
HS-HPT	High-Speed High Pressure Torsion
HTP H-	Tube Pressing
IDB	Incidental Dislocation Boundary
IDC	Isolated Dislocation Cell
I-ECAP	Incremental ECAP
LSEM	Large Strain Extrusion Machining
MAIFS	Multi-Axial Incremental Forging& Shearing
MSB	Micro Shear Band
NDMX	Nanodynamics High Performance
NP	Number of publication
NRE	Nonlinear Rotary Extrusion
OIM	Orientation Imaging Microscopy

PFM	Plastic Flow Machining
PSE	Pure Shear Extrusion
PTCAP	Parallel Tubular Channel Angular Pressing
PTE	Planar Twist Extrusion
RCS	Repetitive Corrugation & Straightening
RF	Repetitive forging
RT	Rotary Extrusion
RUE	Repetitive Upset Extrusion
SCAP	Symmetrical channels angular pressing
SFE	Stacking Fault Energy
SFT	Stacking Fault Tetrahedron
Sp-ECAE	Spiral Equal Cannel Angular Extrusion
SPD	Severe Plastic Deformation
SRAR	Single-Roll Angular-Rolling
SSE	Simple Shear extrusion
STS	Severe Torsion Straining
TCAP	Twist Channel Angular Pressing
TCAP	Tube Channel Angular Pressing
TCEC	Tube Cyclic Extrusion-Compression
TCMAP	Twist channel multi-angular pressing
TE	Twist Extrusion
T-ECAP	Torsional-equal channel angular pressing
TEM	Transmission Electron Microscopy
HPS	High-Pressure Shearing
TSP	Tube Channel Pressing
TST	Tandem Process of Simple Shear Extrusion & Twist Extrusion
TWIP	Twinning Induced Plasticity
UDW	Uncondensed Dislocation Wall
UFG	Ultrafine-Fine Grained
VE	Vortex Extrusion

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1. Introduction

During the last two decades, severe plastic deformation (SPD) has attracted the increasing attention of the research community due to its potential for the fabrication of bulk nanostructured and ultra-fine grained materials [1]. Several advantages of SPD methods together with the unique physical and mechanical properties inherent to nano/ultra-fined grained materials have caused the specialists' interest to grow remarkably toward the characterization, modification and development of new SPD methods [2,3]. The historical development in SPD processing has been categorized by Langdon into three ages [4]: the ancient age, the scientific age and the microstructural age. According to the Langdon's report, the artisans were the first that utilized the fundamental principles of this type of metal processing in the ancient times. During the Han dynasty around 200 BC, the local artisans in ancient China developed a forging process in order to introduce substantial hardening of steel for use in swords. This technique consisted of a repetitive forging and folding to produce high strength steels. This technique was then expanded to produce Damascus steel in ancient Syria and Wootz steel in ancient India.

The start of the scientific age goes back to the pioneering work of Bridgman [5]. Bridgman combined the compression and shear deformation to investigate the effects of high pressures on bulk metals [6]. The achievements in this field led to his winning of the Nobel Prize in physics in 1946. Further development of this method, presently known as High-Pressure Torsion (HPT) [7], was conducted in formerly Sverdlovsk in the former Soviet Union [8]. Thereafter, in the 1970s and 1980s at an institute in Minsk in the former Soviet Union, Segal and his co-workers introduced a novel forming method, known as equal-channel angular pressing (ECAP), in order to impose high strains into the metal billets by simple shear [9]. Despite the basic innovation during the scientific age, the main attention was directed to the development of material processing and little attention was given to the microstructural features of the SPD processed metals.

The situation was changed during the microstructural age when new and advanced tools such as transmission electron microscopy (TEM), high-resolution TEM, electron back scatter diffraction (EBSD), orientation imaging microscopy (OIM) and modern X-ray analysis were innovated. The first developments and investigations of nanostructured materials processed by SPD methods were fulfilled by Valiev and his co-workers in Ufa in the early 1990's [10]. In fact, through several publications, Valiev and his co-workers demonstrated the potential for using SPD process to produce nanostructured and ultrafine-grained metals with new and unique properties [11]. Subsequently, the microstructural features of nano/ultra-fine grained materials fabricated by SPD were progressively of more interest to various scientists around the world outside of Russia [12].

At present, besides the numerous published works on microstructural evolution during SPD processing, very different and new SPD processes have been developed and evaluated. The most common and popular SPD methods are HPT [13,7], ECAP [9,12] and accumulative roll bonding (ARB) [14]. Though the growing interest in SPD processing is limited only to the last decade, this subject area has made a remarkable impact on published works within the scientific community. This is proved by considering the increasing number of publications high numbers of citation, numerous specific conferences, workshops and symposia on the subject of SPD process. Therefore, the present authors believe that in recent years a new age, named as progressive age, has started for SPD processing. This age is characterized by unusual properties of processed materials, powder consolidation, composite production and simulation on the one hand, and by the development of new SPD methods on the other hand. Regarding the rapid developments during the progressive age of SPD processing, an examination of its impact on the scientific community with emphasis on the contribution of various countries, new achievements and new SPD methods needs to be conducted.

To date several review papers have been published in this subject area. Some of them characterize the aspects of a particular SPD method such as ECAP [15,12,16-19] and HPT [7,13,20,21], others investigate the nano/ultrafine grained characteristics of SPD methods [7,12,22,15,23-25,3] and the rest consider the new SPD methods that have been developed so far [26]. Regarding several review papers published in this field, the present overview is an attempt to provide some other aspects of SPD methods to which little attention has been paid. These aspects includes the SPD research status in the world, new concepts of grain refinement, collection of all invented SPD methods and new aspects of SPD application.   Therefore, in one section, the impact and status of the SPD on the research community are evaluated by considering the contribution of the top-ranked countries. For this purpose, all data are taken from Thomson Reuters ISI Web of Science. In another section, the microstructural evolution during SPD is reviewed by considering several new concepts such as grain refinement by twining, grain growth due to the strain reversal and grain growth because of the large plastic strains. In the next section, all methods of SPD that have been proposed and developed so far are introduced based on a new classification. This section provides a comprehensive source available to cover most of the SPD methods presented up to now. Finally, the potential of SPD methods for practical applications is presented.

2. The SPD research status in the world

Over the past three decades, producing bulk ultrafine-grained (UFG) and nanostructured materials through the application of SPD methods has attracted a considerable interest in the field of materials science and engineering [17,20]. Based on Thomson Reuters, more than 10000 researchers from 80 countries have contributed to the investigation and development of SPD methods. However, just about 1400 researchers have published more than 5 documents (>0.05%). In addition, in terms of the contribution of different countries, just 32 countries have published more than 40 items (>0.5%). This depicts the importance of SPD in these countries. Fig. 1a shows the ranking of countries according to the total number of publications (NP) in the field of SPD in two different periods of 1990- 2018, and 2008-2018 based on Thomson Reuters ISI Web of Science. According to the total NP up to the end of May 2018, in general, researchers from Russia, China, USA, Japan and Germany have published the highest number of articles. However, the position of countries has changed during the recent decade. China, Russia, USA, Japan and Iran are the first countries during 2008-2018.

The total NP is not a comprehensive measurement to assess the impact and the quality of the publications. To compare the quality and impact of the publications, the *h*-index and the average number of the times a document has been cited for the publication during 2008-2018 (by the first ten countries in the field) are illustrated in Fig. 1b. In accordance to this figure, the highest values of h-index are attributed to researches from the USA, Japan, England, Russia, and Germany. On the other hand, according to average citation per article, England, Australia, USA, Japan and Germany are on the top of the list. Considering both the total number of publications and the number of citations (Fig. 1a and Fig. 1b), it is seen that despite the high number of publications from some countries like China, Iran, and India, the h-index and the average citation to them are relatively low. This can be attributed to the difference in the visibility and the importance of publications due to several reasons.

The visibility of a research arises from two factors including its presentation in the international conferences and collaboration with researchers from other nations. Attending international conferences is an important way for scientists to introduce their new achievements to colleagues from other countries. Therefore, the visibility of the documents can rise by participating and presenting articles in international conferences. In addition, discussions after the presentation, with other colleagues can lead to the improvement of the presented research and also future works. Therefore, the investigation of the total number of documents published in the proceedings is a good measurement to check the visibility.

Based on this argument, the documents are divided into different types including original journal articles, conference proceedings, review articles and book chapters. The fraction of various types of published documents by the researchers for some of the most important countries in SPD is shown in Fig. 2. Interestingly, the highest number of review papers and book chapters has been published by researchers from USA, Russia, Germany and Australia while the Russians and the Japanese have the highest fraction of articles presented in conferences. As shown in Fig. 1b, these countries have the highest value of *h*-index.

Another indication of the visibility of the articles that leads to higher numbers of citation is the collaboration with other scientists. The collaboration of various countries in the field of SPD up to the end of 2017 for the top 15 countries in the field of SPD is plotted in Fig. 3. The countries are specified by circles and their collaborations are denoted by the solid lines. The countries of each continent are indicated by a specific color. The size of each circle is an indication of the collaboration of that country with the other countries. The higher number of articles published in collaboration with scientists from other countries causes the circle to be larger. It is obvious that England has the highest collaboration and Australia and Germany are ranked after. It should be pointed out that England is an exception, because Langdon, who has a high number of publications in SPD, has two affiliations with the University of Southern California and the University of Southampton. Interestingly, countries like Australia and South Korea with a low number of proceedings papers (Fig. 2), have relatively high collaboration (Fig. 3), which may result in the high rank of these countries based on citation (Fig. 1b). Another interesting feature of this map is the low collaboration of Asian countries.

Since the invention of ECAP in 1981[9], it has attracted the attentions of many from materials scientific community that results in more than 5000 published documents. The large number of publications in this filed has made ECAP the most popular SPD method. Referring to Fig. 4a, the USA, China and Russia are the first countries in the world with more than 900, 900 and 700 NP, respectively. By limiting the scope of the search to 2008-2018, China becomes the first following by Russia and the USA. Interestingly, the highest progress attributes to Iran. While Iran ranks the ninth during the total period, it climbs in the list and becomes the fourth in the period of 2008-2018. A closer look at the variation of NP during this period indicates that in the USA, Japan, South Korea and Germany, the NP in the field of ECAP decreased from 2008 to 2018 and the NP remained approximately constant in Russia, China and Czech Republic. Iran is the only country that retains its progress and its NP increased gradually from 2008 to 2018. To compare the quality and impact of the publications in the field of ECAP, the rank of countries according to the h-index and the average number of times an item has been cited for the total number of documents during 2008-2018 is shown in Fig. 4b. Studies conducted in England, the USA, Germany, Australia and Japan have received more attention.

The second popular method of SPD is HPT with more than 2800 published documents up to now. In HPT, a specimen is subjected to torsional shear straining under a high hydrostatic pressure [13,20,21]. HPT is usually applied to the disk-shaped specimens [20], though HPT processing of the cylindrical [27,28] and the sheet samples [29] has been reported outstandingly. The HPT method was first introduced by Bridgman in 1935 [13]. However, the importance of HPT in SPD community mainly comes from the report of Valiev and his co-workers in 1988 [30]. According to Web of Science, from that time to 2018, most of the researches in this field have been performed in Russia, USA, China, Japan and England (Fig. 4c). As shown in Fig. 4c, the same trend is seen in the recent decade (2008-2018). An interesting feature of this figure is that, by comparing this figure with Figs. 1a and Fig. 4a, the first-ranked countries in SPD and also in ECAP and HPT are the same but they appear in a different order. The rank of countries according to the *h*-index and the average number of times an item has been cited for the total number of documents in HPT are shown in Fig. 4d. As can be seen, publications from USA, Japan, England, Russia, and China have the highest *h*-index. Regarding the average number of citation to an article, England, the USA, and Australia are the firsts in the ranking. This confirms the high quality of the researches conducted in Australia, despite the low number of publication in this field.

In addition to ECAP and HPT, ARB (invented in 1998) [14] is another popular method of SPD. Up to now, more than 900 documents have been published in the field of ARB. As illustrated in Fig. 4e, Iran and Japan have the first and second rank in the world with 247 and 202 records in ARB, respectively. The third position is held by China with approximately half the number of the publications of Iran and Japan. This indicates that ARB has attracted considerable attention from Iranians considering the fact that ARB in Iran began 10 years after the first efforts of the

Japanese in this field. The rank of countries in ARB does not change significantly during the recent ten years. Compared with ECAP and HPT, it is seen that Russians are not interested in ARB in spite of their high tendency to the other methods. In Contrast, several researchers from other countries that have a contribution in field of ECAP and HPT, are interested in ARB too. For instance, researchers from Canada and Denmark have published considerable number of articles in the field. Looking to the average citations and *h*-index of the publication during 2008-2018 (Fig. 4f), it is observed that the publications from Iran, USA, Japan, Germany and Australia could attract the most attention through the scientific community.

3. Microstructural evolutions by SPD

The SPD induced structural evolution and the corresponding deformation mechanisms have been investigated extensively. Not only did the studies confirm the grain refinement in SPD products, but also they expressed the occurrence of grain growth depending on the grain sizes at the time of the deformation and the deformation conditions. In this section, the mechanisms of grain refinement and grain growth by SPD processing are discussed.

3.1. Grain refinement

A large number of works and review papers have been published to describe the mechanisms of grain refinement in SPD processing. Therefore, this paper presents only some generalized mechanisms to complete the academic history of the current work. The mechanism of grain refinement during SPD is controlled mainly by two main factors: process parameters including the strain, strain rate, temperature and deformation path and materials parameters such as initial grain size and stacking fault energy (SFE).

Tao and Lu [31]have shown that grain refinement through dislocation glide and twinning are two competitive mechanisms of grain refinement in FCC metals. They state that the strain rate and temperature are two important process variables that control the mechanism of microstructural refinement during plastic deformation. In order to combine the effect of temperature T and that of the strain rate ε° they used Zener-Hollomon parameter, $Z = \varepsilon^{\circ} \exp(-Q/RT)$ where R is the gas constant and Q is the activation energy for deformation. Their results showed that by increasing Z (i.e., increasing strain rate and/or decreasing temperature) the refinement by twinning mechanism becomes more dominant. They also indicated that at a critical Z*, which designates a critical strain rate and/or a critical temperature, a transition in the dominating refinement mechanism from slip by dislocations to twinning occurs. The critical Z* depends on the SFE, a material parameter, that crucially determines whether the deformation occurs by slip or twinning. The deformation by twining is dominated at low to medium SFE even at low strain rates or at high temperatures. In contrast, the deformation mode in high SFE materials is controlled by slip even at relatively highs train rates and/or at low temperatures. Therefore, it can be concluded that Z* increases with increasing SFE (Fig. 5). For low SFE metals, the structural refinement is dominated by twinning even under low Z conditions, for medium SFE metals the twining mechanism may be active just under high Z values and for high or very high SFE metals the grain refinement occurs through dislocation activity even at high Z conditions.

In addition to SFE, the initial grain size can also affect the mode of deformation and determines the mechanism of grain refinement. It has been shown that by changing the microstructure from coarse grain to ultrafine or nano-structure, the possibility of deformation by twinning becomes more effective. In other words, by reducing the grain size, the mechanism of grain refinement through twinning is more likely to be dominant. It has been concluded that the variation in Z* with SFE (i.e., Z*-SFE line in Fig. 5) can be shifted to the right when the grain size is reduced.

3.1.1. Grain refinement by dislocation activity

Dislocation activity that results in grain refinement is mainly categorized as dislocation gliding, accumulation, interaction, tangling and spatial rearrangement. There have been a number of models such as Sach's zero constraint [32], relaxed constraint [33], and Taylor's full constraint [34] models. However, the most pronounced one, particularly for equiaxed grains, is Taylor's model in which strain compatibility is achieved through simultaneous operation of at least five slip systems [34,35]. With the acknowledgment of Taylor's model, the so-called grain subdivision mechanism has been proposed [36]. During plastic deformation, the non-equilibrium grain boundaries formed by dislocation accumulation are the key factor for structural characterization [1] because at large strains the microstructure contains very high fraction of high angle grain boundaries. Fig. 6 illustrates a schematic model for the formation of non-equilibrium dislocation boundaries during SPD. During plastic deformation, the non-equilibrium grain boundary introduces an excess energy and long range elastic stresses.

The progressive accumulation of dislocations into dislocation boundaries results in the formation of two types of dislocation boundaries with different structure and morphologies [37]. One is the incidental dislocation boundaries (IDBs) that are formed by mutual trapping of glide dislocations subdivide the grains into cells. These boundaries have mainly a tangled dislocation structure. Geometrically necessary boundaries (GNBs) are another type of dislocation boundaries that are formed due to the activation of different slip system in adjacent grains or due to partitioning of total shear strain among a set of slip planes. These types of boundaries subdivide the grains into cellblocks and are nearly planar boundaries with a regular dislocation structure. With increasing the plastic strain, the boundary spacing of both IDBs and GNBs decreases whereas their misorientation angle increases. However, the rate of change of boundary spacing and misorientaion angle of GNBs is higher than that of IDBs. At large strains, a high fraction of dislocation boundaries, particularly GNBs, change their misorientation into the high angle grain boundaries and an ultrafine-grained structure is formed. The gradual change of the dislocation boundaries produced at low strains into the high angle boundaries at large strains is called the in-situ or continuous dynamic recrystallization [38]. The characteristics of this type of mechanism are that at large plastic strains the microstructure contains a wide distribution of misorientation angles and the low and high angle grain boundaries are spatially mixed throughout the structure. TEM image of the microstructure of pure Al after six cycles of ARB is presented in Fig. 7 as an example [39]. The misorientation map of the framed area is also included.

Another key factor in the grain refinement is the initial grain orientations. Based on a mechanism proposed by Xue et al. [40] for the grain refinement of OFHC Cu in the first pass of ECAP, the initial orientation of the grains affects the grain refinement (as shown in Fig. 8). This model explains that the microstructural changes in the first ECAP pass usually contains four stages: "dislocation generation" (Fig. 8b), "dislocation cell construction" (Fig. 8b), "self-organized gliding along the main slip planes and an elongated laminar structures (ELS) formation (Fig. 8c)", and the "possible formation of a second set of ELS and/or secondary microbands" (Fig. 8d). They concluded that all the ELSs were found to develop on {1 1 1} planes. They often appeared to have their boundaries either nearly parallel or perpendicular to the micro shear bands (MSBs).

Moreover, it is well discovered that the final dimension of refined grains is directly associated with some initial substructure characteristics prior to reaching the MSP. According to the model proposed by Sakai et al. [38,39,41,42] (Fig. 9), MSBs develop and cross each other to form equiaxed structure at intersections and later along the bands. Further processing increases the density of MSBs to reach an equiaxed structure with ultrafine grain size. In fact, the minimum grain size achieved by a specific SPD process is determined through the development of a dynamic balance between dislocation generation and dislocation recovery [7].

The authors would like to refer the readers to the fact that IDBs and GNBs are general terms and if one likes to investigate the boundaries in more detail, he/she should consider five dislocation structures that have been detected in severely deformed materials by Huang et al. [35]. These include clustered-small-cell wall (CSCW), uncondensed dislocation wall (UDW), isolated dislocation cell (IDC), dense-dislocation wall (DDW), and dislocation tangle zone (DTZ). A TEM image of nanostructured Cu subjected to RCS process containing various types of boundaries is shown in Fig. 10. Usually DDWs, UDWs and CSCWs are observed in GNBs. The CSCWs are similar to the micro shear bands defined by Hansen *et al* [43,44]. Although DDWs and CSCWs have been detected in both rolled and severely deformed microstructures, IDCs, UDW and DTZs have not been observed in rolled microstructures. It should be pointed out that UDWs and DTZs have been detected in fatigued polycrystalline copper [45]as well.

3.1.2. Grain refinement by twinning

This mechanism is important in metals with low to medium SFE particularly at high strain rates and/or at low temperatures when the critical shear stress for twinning is lower than that of dislocation glide. According to this mechanism, plastic deformation causes the formation of several deformation twins within the coarse grains. The average spacing between adjacent twin boundaries may be in the nanometer scale and twin/matrix (T/M) lamellae with a nanoscale thickness [46].

Based on the development of deformation twin structures in various FCC metals, Tao and Lu [31] proposed four different mechanisms for grain refinement through twining. These mechanisms are twin/lamellae (T/M) fragmentation, formation of twins, twin/twin intersection and shear banding of T/m lamellae. Fig. 11 illustrates the schematic models and the corresponding TEM images of four structural refinement mechanisms. According to the first mechanism, the T/M layers are fragmented by the accumulation of dislocations and formation of IDBs within them (Ia). With increasing the strain, the misorientation angle of the IDBs increases and at the same time, twin boundaries lose their coherency due to the absorption of more dislocations (Ib). This mechanism has been observed in Cu deformed through surface mechanical attrition treatment process at ambient temperature (Ic) [47]. In the second mechanism, the formation of the secondary twins within the T/M lamellae plays a significant role in twin layer subdivision (IIa) and as before the interaction of dislocations with twin boundaries results in incoherency across the refine volumes (IIb). The formation of secondary twins within the T/M lamellae has been observed in the surface layer of a surface mechanical grinding treatment Cu sample (IIc) [48]. The third mechanism can occur in the FCC metals that have low SFE. According to this model, the formation of multiple twins inside the T/M lamellae (IIIa) subdivides the twin layers into smaller blocks (IIIb) with high misorientation. A typical TEM image of multiple twin formation after surface mechanical attrition treatment of 304 type stainless steel is shown in (IIIc) [49]. According to the fourth model, the localized deformation in the form of shear banding takes place across the T/M lamellae (IV a and b). The formation of nano-sized and equiaxed grain with random orientations in the shear zone is the responsible mechanism for grain refinement. The experimental evidence of the formation of shear band within the T/M lamellae in a dynamic plastic deformation Cu is shown in IVc [48].

3.2. Grain growth

There is always a minimum average grain size achieved after a specific SPD processing of a specific material (usually after several passes). The minimum average grain size is a function of process parameters and materials parameters. The minimum grain size is achieved by the dynamic balance between the grain refinement process and the grain growth process which is evident in SPD processes [50]. In addition to the grain growth due to the large deformation, there are a few recent reports that show the grain growth as a consequence of strain reversal during SPD processes. In the following, the plastic deformation induced grain growth in two levels of deformation is explained, in early stages of SPD in some non-monotonic processes and less than a minimum average grain size (in high strains).

3.2.1. Grain growth as a consequence of shear strain reversal

Although the role of strain reversal in softening (Bauschinger effect) and the resulting structure have been studied sufficiently for fatigue test conditions, but the plastic strain in fatigue tests is lower than 1% and it is of great importance to investigate the effect of strain reversal in SPD processes. A few articles have studied the effect of shear strain reversal on microstructural evolution during various SPD processes. For example, the effect of strain reversal during HPT was investigated by Horita and Langdon [51] in 2005, Wetscher and Pippan [52] in 2006 and Orlov et al. in 2009 [53]. One of the most comprehensive studies on the effect of shear strain reversal on the microstructure and texture of SPD processed samples has been published in a set of publications during 2016-2018 by Bagherpour et al. [54-58]. They deformed pure Cu samples by a single pass of simple shear extrusion (SSE) process, which interestingly contained shear strain reversal. Using TEM, STEM and EBSD investigations, they calculated the grain size, texture and dislocation density of the samples during the process in regions of both forward and reverse shear and proposed a model for the microstructural changes during shear strain reversal.

The proposed model for the microstructural evolution during SSE processing can be generalized to every process such as TE and ECAP in route C in which shear strain reversal is inherent (non-monotonic processes). The model is an extension to rotational (in-situ) recrystallization [59] in the presence of shear strain reversal. Fig. 12 illustrates a schematic of the model. As it was discussed in the previous sections, the grain subdivision is the main mechanism in the forward shear and consequently elongated cells with interconnecting subgrains are formed gradually during forward shear. By reversing the shear, the dislocation fluxes are reversed leading to the reduction of the stored excessive dislocations introduced in the boundaries by the activation imbalance and also resulting in disintegration of the misfit dislocations. In addition, the cyclic behavior of the SPD process retarded the formation of HAGBs as a consequence of a kind of Bauschinger effect. For Cu during one pass of SSE, the dislocation density decreased by ~14%, cell wall became thicker by 20% and the lamellar boundary spacing increased by 12%, as a result of shear strain reversal [54]. In general, shear strain reversal during the SPD process have four main consequences: i) the inclination angle between the boundaries and the shear direction increases; ii) the total amount of HAGBs is reduced; iii) the cell walls become thinner and iv) the dislocation density decreases.

Furthermore, the effect of shear strain reversal on the texture changes of the pure copper during a single pass of SSE has been investigated by finite element analysis [58] and examined experimentally [55]. It has been shown that the simple shear texture is formed gradually in the forward shear. However, the degree of the simple shear texture decreases gradually by shear strain reversal while the major components are still simple shear texture after the end of the process. It must be pointed out that the texture after the end of the processes that contain shear strain reversal depends on the magnitude of both forward and reverse shear.

It is clear that the mechanism of grain growth by shear strain reversal for fcc metals is well developed. However, for other metals, bcc or hcp ones, the occurrence of grain growth in the presence of shear strain reversal and its mechanism require more investigations.

3.2.2. Grain growth in large strains (low grain sizes)

During each SPD method, the grains can be refined to a specific size depending on the stacking fault energy of the material. That is, further processing of the material by SPD method cannot refine the grains anymore. For a specific material, the minimum grain size achievable in a SPD process is controlled by a dynamic equilibrium between the grain refinement and grain growth, which depends on the intrinsic material properties (stacking fault energy, purity, melting temperature, etc.) and extrinsic processing parameters (temperature, strain rate, amount of hydrostatic pressure, deformation mode, etc.) [56]. Plastic deformation- induced grain growth has been widely reported in various SPD methods including HPT [60-63][64-67], ECAP [12,50,64], ARB [65,66] [70,71] and SSE [56,57]. Different mechanisms has been proposed for the strain induced grain growth in nanocrystalline (NC) materials that include the rotation of nano-grains and propagation of shear bands [67], grain boundary migration [68] and stress coupled grain-boundary migration (a grain grows at the expense of other neighboring grains) [69].

One of the promising mechanisms for the strain induced grain growth has been proposed in 2008 by Wang et al. [60,70]by using a nano-beam electron diffraction investigation of nanocrystalline Ni in response to the in-situ tensile deformation under TEM. A schematic of the model, which is based on the grain rotation, is illustrated in Fig. 13. Consider a nanostructured material with high-angle grain boundaries for the original material, as shown in Fig. 13a. Because of plastic deformation, a relative shear between grains 1 and 2 occurs along their boundary through grain boundary dislocation glide. At the same time, grain rotation in the neighboring grain 3 takes place because of climbing grain boundary dislocations (Fig. 13b). Climb of grain boundary dislocations results from the splitting of gliding grain boundary dislocation at triple junction into two climbing grain boundary dislocations [71]. By additional deformation, the other grains adjacent to grain 3 (e.g., grains 1 and 2) rotate in order to reduce the grain boundary angles and to form grain agglomerate (Fig. 13c). As shown in Fig. 13d, with further plastic deformation, grain coalescence occurs by merging the neighboring grains into a large grain and this completes the grain growth.

After accepting the occurrence of grain growth in nanocrystalline materials when reaching a certain grain size, it is essential to find the methods to detect this phenomenon and to define this certain grain size. The authors wish to draw attention to the point that the exact detection of the growth of a special grain is almost impossible unless for a researcher who has access to the in-situ TEM investigations. However, it is generally accepted that there are some other microstructure pieces of evidence that would be detected only after achieving the critical grain size and at the onset of grain growth or afterward. Therefore, it is legitimate to relate the observation of these evidences to the occurrence of grain size in spite of the fact that they are not necessarily due to the grain growth. Considering this, two main questions are raised in mind, including: i) what are these microstructural pieces of evidence? and ii) what is the minimum average grain size below which grain growth occurs? These ambiguities will be clarified in the following paragraphs.

One indication of grain rotation is the formation of Moiré fringes caused by the small angle misorientation of neighboring grains [60]. A TEM image of a Moiré fringes detected in a pure Cu samples severely deformed by 12 passes of SSE, is shown in Fig. 14a . It should be pointed out that in this sample a grain growth of ~5% is seen in the sample of 12 passes in comparison to 8 passes [56]. Another indication of the achievement of the minimum grain size in nanocrystalline fcc metals is the formation of twins, which occurs for these materials at room temperature and low strain rates. This phenomena has been described by three distinguished mechanisms including consecutive “partial dislocation emission from grain boundaries (GBs) and GB junctions” [72,73], “dynamic overlapping of stacking faults results in nucleation of twins inside grains” [74] and “twin lamella formation via the dissociation and migration of GB segments” [75]. However, a large amount of plastic deformation is the prerequisite to initiation of twining. Fig. 14b shows an example of such a deformation twins with twin boundary spacing (λ) measured as ~12 nm. It is initiated from GBs and extended via partial dislocation emission from the neighbor (111) slip plane in Cu samples severely deformed by 12 passes of SSE.

The other sign of attaining the minimum grain size is indicated by stacking fault tetrahedra (SFT), a common type named vacancy clustered defects, which is believed to be formed by the Silcox-Hirsch mechanism [76]. SFTs with sizes of 4–14 nm and an average value of about 7 nm in a grain of Cu detected in a severely deformed sample of 12 passes of SSE are shown in Fig.

14c. Bagherpour et al. [56] found SFTs only in grains that are confined by well-developed sharp grain boundaries. These kind of boundaries have been observed in dynamically recovered or even partially recrystallized grains and raised from substantial stress relief.

One method to predict the onset of growth is to predict the certain grain size (d_c) below which the nano twins can be formed. Huang et al. [77] proposed a relationship for the d_c as

$$d_c = \frac{2\alpha G(nb - b_1)b_1}{\gamma_{SFE}} \quad (1)$$

where n is a stress concentration factor, b is the Burgers vector of the full dislocation, b_1 is the Burgers vector modulus of the Shockley partial dislocation, G is the shear modulus, γ_{SFE} is the SFE of the metal and α is a parameter reflecting the character of the dislocation. However, it is not always easy to measure the SFE for the specific material. In 2017, Bagherpour and his coworkers [56] proposed a relationship between γ_{SFE} and the maximum size of SFTs (l_{max}) as

$$\gamma_{SFE} = \frac{2G(b_3^2 - 2b_2^2)}{\sqrt{3}l_{max}} \quad (2)$$

in which b_2 is the Burgers vector modulus of stair-rod dislocations (with Burgers vector of a/6[110]) and b_3 is the Burgers vector modulus of Frank loop (a/3<111>) dislocations. They derived this equation using the energy balance between the total energy of the tetrahedral defect and the total energy of the triangular Frank loop and determined the critical grain size to achieve nano twins as below

$$d_c = \frac{\sqrt{3}l_{max}(nb - b_1)b_1}{(b_3^2 - 2b_2^2)} \;. \quad (3)$$

4. Classification of SPD techniques

Due to the interesting properties of ultrafine-grained/nanostructured metals processed by SPD techniques, many investigations have been dedicated to new roots for processing materials by SPD as well as the modifications of the current available techniques. These developments have made it possible to conduct SPD by different deformation modes on metallic materials with different shapes/geometries (rods, bars, billets, tubes and sheets).

So far, there have been many reports on different SPD techniques and some review papers have been dedicated to this topic [7,12,22,15,23,26,24,25,3]. However, these papers have covered only a group of SPD techniques and there is no comprehensive source available to cover most of the SPD methods presented so far. Therefore, several duplications have occurred in a field in which a unique technique is presented with different names and by different groups of researchers. This can happen because the authors, for instance, have not been aware of the presence of such a technique before. Therefore, this section tries to fill this gap by providing a comprehensive source of SPD techniques and their modifications over the course of years as well as the very recent ones. This can lead to a useful reference for researchers working in this field.

Due to the numerous number of SPD techniques presented so far, these techniques are presented in separate tables, which are categorized based on the processing method as follows:

1- SPD techniques based on equal channel angular pressing/ECAP

2- SPD techniques based on torsion/shear under high pressure

3- SPD techniques based on direct/indirect extrusion

4- SPD techniques based on pressing/forging

5- SPD techniques based on rolling

6- Combined SPD techniques

In this section, the authors try to collect (in the following tables) all conventional, modified and combined techniques that have been introduced as SPD method so far. The presented references can guide the readers to follow each technique/modification and consequently find more information/references on that topic.

By investigating the first publications on each method, the countries, which have contributed to the introduction of each method, can be found. In table 1, all the collaborations of the countries in the mentioned categories are summarized by counting the number of the contributions for each country. Although 19 countries are involved, more than 70% of the innovations come from only 7 countries including Iran, Japan, China, the USA, South Korea, the UK and Poland. As shown in Fig. 15, Iran, Japan and china with 20%, 14% and 14% of the total contributions, respectively, are the first countries in this regard. Iran is the only country that has contributed to all the categories.

Table 2 provides different techniques which are presented for SPD processing using the principles of equal channel angular pressing (ECAP). In most cases the main objectives for presenting these various techniques are:

1- Providing the possibility of continuous processing of samples (for long samples).

2- Increasing the grain refinement efficiency of ECAP.

3- Performing ECAP on samples with various shapes/geometries.

In addition, some modifications have been carried out in the design of ECAP to increase the process efficiency by decreasing the processing load or increasing the homogeneity of the processed samples. Some examples are presented in the same table. As can be concluded, most of these modifications have been done in Japan and UK.

The authors would like to draw the attentions of the readers to the fact that the mode of deformation in all of the mentioned methods in the Table 2 is similar to that of ECAP. This can be concluded by a close look to the geometry of the dies and tools in almost all of the methods. However, the similarity of the process of "large strain machining" to ECAP is not as clear as the rest of the methods. To clarify this, a more detail investigation of the deformation mechanism through the process is of great advantage. The plane-strain machining is considered by a sharp, wedge-shaped tool that is used to remove a specific depth of a material. This is achieved by the movement of the tool in a direction perpendicular to its cutting edge. In the orthogonal cutting process, material is severely deformed at a very narrow zone in front of the tool tip. In 1945, Merchant [78] proposed that the whole shear strain is imposed on a certain plane called a "shear plane". Fig. 16a, illustrates the position of the shear plane in addition to the general deformation model for orthogonal cutting. As observed, the shear plane in the "large strain machining" is similar to that of ECAP, which can be found in Fig. 16b. This is the main reason that the authors put the process of "large strain machining" in the category of the methods based on ECAP.

Since tubes are the most practical essentials in aerospace, automobile, building construction, petroleum industries, etc. [122], it is sensible to pay further attention to fabricate tubular UFG materials. Whereas most of the techniques in Table 2 are capable to process billets or bars, some of them, including ECAP are used for processing of tubular samples [114,115]. tubular channel angular pressing (TCAP) [121], tube channel pressing (TCP) [122,123], and parallel tubular channel angular pressing (PTCAP) [124], are designed to fabricate the nanostructured tubes from the initial tubular work pieces. The considerable Iranians' attention to tubular UFG samples may come from the fact that Iran is in the second place in the production of natural gas. Furthermore, petrochemical industries are the biggest companies in Iran. Hence, researches in the development of tubular sections can attract more funds from both companies and government. Another promising aspect of the methods based on ECAP, is its ability to continuous processing of the pieces. These methods are conshearing process [82], continuous confined strip shearing (C2S2) [83-86], ECAP–Conform [87], Multi ECAP Conform [91], and continuous frictional angular extrusion [90]. Therefore, the continuity of the process and its ability to process work pieces with different shapes and geometries are some of the key factors that make ECAP as a good candidate for industrial uses.

Considering the high efficiency of high pressure torsion (HPT) in grain refinement, many efforts have been conducted to scale up the sample size as well as the application of a similar deformation mode on samples with various geometries (other than disks) like tubes, rings, rods and bars. Table 3 summarizes some of these techniques. Similar to the methods based on ECAP, researchers from Japan are pioneers in the methods based on high pressure (Table 1).

In the SPD techniques illustrated in Table 4, the work piece is pushed to pass through a die with special design/geometry with a direct/indirect extrusion channel. However, after the process, the sample retrieves its initial geometry, which makes it possible to repeat the process for several times. Therefore, a high level of strain can be accumulated within the sample, and consequently, a significant structure evolution happens. Most of these techniques can be easily installed on any available pressing/direct extrusion facilities. Iranian scholars with more than 30% of the contributions in these methods are the first in the world.

Among all of the methods based on extrusion, twist extrusion (TE) and simple shear extrusion (SSE) attracted most attention. For instance, the microstructural changes and mechanical behavior of pure aluminum [146-148], pure copper [54-57,149], twinning induced plasticity (TWIP) steel [150,151,149,152] and pure magnesium [153-155] after SSE processing was studied experimentally. Besides, a number of studies have simulated the process by finite element (FE) analysis and/or crystal plasticity FE [156,146,147,58,157,158].

The SPD techniques, which can be considered as open/closed die forging techniques, are summarized in Table 5. These techniques are designed for giant straining of samples, generally, by repeating the process (pressing/forging) on different sides of the sample. A few numbers of countries including China, the USA and Iran have contributed to these methods and have been the most active ones. Accumulative roll bonding (ARB) [14] is a well-known effective technique for SPD processing of sheet materials. However, there are other alternatives for SPD processing of sheet materials by rolling, which are presented in Table 6.

To increase the efficiency in SPD processing, some SPD/forming techniques have been combined in a single die / set-up which are presented here as “combined SPD techniques” (Table 7). These methods benefit from the simultaneous application of different deformation modes in addition to the high strain value accumulated within the sample during processing using the combined techniques. Therefore, these techniques can generally result in a structure with smaller grain size and with a more homogeneous grain size distribution compared to the results, which could be obtained after processing by each process alone. These methods attracted the attention of Iranian researchers rather than that of the others (Table 1).

Although SPD techniques are generally designed in a way to retrieve the initial geometry of the samples, the initial geometry of the processed sample is not retained after processing by single pass SPD techniques. Single pass SPD techniques, however, are capable of introducing relatively large plastic strains by combining different modes of deformation that can result in smaller grains with a high fraction of HAGBs compared to those of the conventional forming operations (like extrusion or rolling). The single pass methods, which can be found in Tables 2-7, are : non-equal channel angular pressing /channel angular deformation (CAD) [116,117], double change channel angular pressing [118], ECAP forward extrusion (ECAP-FE) [231], forward extrusion ECAP (FE-ECAP) [232], incremental angular splitting [119], torsion extrusion [240,241], vortex Extrusion (VE) [188,189], variable cross-section direct extrusion (CVCDE) [190,191], gradiation extrusion [192,193], integrated extrusion [194], compound extrusion [195], compound twist extrusion/C-TE (TE+Ext.)[243], alternate extrusion (AE) [196], large strain machining [120] and large strain extrusion machining (LSEM) [245]. It is noted that among all SPD method, friction stir processing (FSP) [144,145] can be categorized as a single-pass or multi-pass process.

5- Application of SPD- processed materials

Despite the extraordinary multifunctional properties of the UFG materials processed by SPD such as high strength, good strength to weight ratio, long fatigue life and the possibility of fabricating cutting-edge products with efficient methods by UFG materials [248], commercial uses of UFG material products are currently rare. As shown in the previous section around 120 variants of SPD methods have been introduced, which shows the great potential of SPD for industrialization. Some market reports documented more than 100 specific market areas for nanostructured metals including automobile, aerospace, electronic devises and defensive and biomedical applications [249,250]. Seventy patents have been issued from 1997 to 2017 in the field of SPD. However, there is still a long way ahead to offer SPD products in the market. The important steps required to achieve this goal are the capability to reduce both, the cost of products and the amount of the waste material, and the ability to produce larger samples (scale-up). The number of patents related to SPD in each year from 1997 to 2017 is shown in Fig. 17. A drastical increase in the number of patents is seen in 2013 and 2014; most of them are about the application of SPD to new materials like Mg, Ti and reinforced metals. On the other hand, the first patents frequently focused on the design parameters with emphasis on ECAP. In this section some of various applications of SPD in commercial uses have been reviewed.

5.1. SPD-processed Al and Cu sputtering targets

The first commercial application of bulk UFG metals returns to 2003 when the sputtering targets for physical vapor deposition were successfully fabricated by scaling up the ECAP technique in Honeywell Electronic Materials [251] in the USA. Honeywell started the scale-up efforts of ECAE in 1997 with the construction of the first production die which has led to several large-scale die sets for different standard sizes of Al, Cu and pure Ti using presses with the capacity of 1000 and 4000 tons (Fig. 18). Most of these dies have been in use on a weekly basis for 6 year [252]. It may be interesting for the readers that the term ECAE (sometimes used instead of ECAP) is a registered trademark of Honeywell International, Inc [12,251]. They offer UFG Al and Cu sputtering targets with a diameter up to 300 mm and a mass up to 32.7 kg. These are produced from plates by ECAP (Fig. 19) monolithically. The monolithic sputtering targets (where the entire target is a mono-block) are used for metallization of silicon wafers in the production of semiconductors. In comparison to the traditional targets (which consists of a target material bonded or soldered to a backing plate made from strong materials like Al 6061 or CuCr), the UFG sputtering targets offers higher lifetime and more uniform deposited coating due to the stronger material and the reduced arcing, respectively, and a better kit utilization. Furthermore, Praxair Electronics by their facilities in the USA, France and South Korea, presents UFG Al and Cu targets (200mm and 300mm in size) with better sputter performance and 65-75% reduction in the ownership cost of such targets [253,15].

5.2. UFG CP Ti for biomedical application

Globally, the rapid growth in the rate of the human population results in the continues increase in the number of elderly people, which in turn leads to the increase in the need for the artificial implantable devices to replace the failed tissues. Therefore, one of the most suitable areas for the application of the UFG materials is in the field of medical implants such as hip, knee and dental implants as well as various screws, plates and meshes used in orthopaedic applications. Popular materials usually used in these applications are cobalt-chrome alloys, stainless steel and titanium alloys. The high strength, good formability, and excellent fatigue and fracture performance of metallic biomaterials (mainly titanium and cobalt chrome alloys) result in the extensive demand of them for surgical implants. In addition to the mentioned properties, high corrosion resistance and low toxicity of the alloys systems that are expected to be used in the physiological conditions, are the favorable properties of them. Therefore, Ti and its alloys have been used widely in implantable devices, which had been forecasted by a US Industry Study [254]. The main advantages of Ti alloys are high corrosion resistance, due to the formation of a very stable passive layer of TiO_2 on the alloy surface, intrinsic biocompatibility, low Young's modulus (twofold lower compared to stainless steel and Co–Cr), resulting in less stress shielding and lower density and producing fewer artifacts on computer tomography and magnetic resonance imaging [255,256]. However, commercially pure (CP) Ti has low mechanical and fatigue strength which is not sufficient for the load bearing implants (orthopedic application) and restricts its application only to dental implants [257]. Alloying by Al and V allows a significant improvement in the mechanical properties, and currently the Ti–6Al–4V alloy is the most extensively used surgical Ti alloy. However, the alloying elements carry the risk of the alloy being toxic for human body as a result of their excessive liberation and accretion in the tissues [255]. To prevail the problem of destructive ion release, enhancement of the mechanical properties of pure titanium by nano-scale grain refinement is an alternative to alloying notion [257,256,255].

Nanostructured titanium has been advanced through the labors of over 160 scientists, engineers, and medical professionals around the world. In 1999, Webster et al. provided the first evidence that osteoblast (bone-forming cells) adhesion and bone formation increases significantly on nanostructured titania compared with conventional titania [258]. Studies of UFG titanium and its special nanoscale structure were begun in 2003 at Purdue University [259] in the USA, and afterward were replicated at research institutions worldwide, each reliably authenticating the positive result that bone cells more rapidly attach to and more readily adhere to UFG titanium than the coarse grain (CG) counterpart. Generally, both *in vitro* and *in vivo* studies have obviously established that nanostructured Ti increases osteoblast cell functions and enhances Osseo integration while at the same time, decreasing bacterial attachment onto the implant compared with CG Ti [260].

To achieve ultra-fine grained structure in CP Ti, both ‘bottom-up’ and ‘top-down’ approaches have been used. Since the current work focuses on SPD methods, which are categorized in top-down methods, we do not consider the bottom-up methods and only focus on the grain refinement during SPD processes; mostly, ECAP [261-264] and HPT [265-267] were used for this purpose. However, there are limited works on the direct application of UFG Ti for medical applications. One of the good examples of such products is a new generation of dental implants under the trademark Nanoimplant (Timplant), which is fabricated in the company Timplant (Ostrava, Czech Republic) and shown in Fig. 20. The processing route consists of ECAP-C for grain refinement and secondary processing of drawing for shaping and additional strengthening following the final process of grinding in order to produce the required surface quality and tolerance [268,256]. As a result, long rods with lengths up to 3 m (Fig. 21), diameters of 4–8 mm, accuracy grade h8 suitable for automation of implant machining, and a uniform nanostructure with a subgrain size of 150–200 nm can be produced. These new generation implants are smaller in diameter (2.4 mm) than conventional implants (3.5 mm) (Fig. 22). The smaller size of the dental implants has two main advantages. Firstly, they can be successfully inserted into thin jawbones where larger implants are not feasible. Secondly, they introduce less damage during the surgery. Presently, these implants have been certified according to the European standard EN ISO 13485:2003 [248]. In another project in the framework of VINAT funded by European Commision and the Ministry of Education and Science of Russian Federation, another implant prototype with the diameter of 2.0 mm with the ultimate tensile strength of 1330 MPa was developed (Fig. 22) [256]. As shown in Fig. 22, this small implant was installed into the jawbone of an 18 years old patient between teeth 11 and 13. Another implant with the diameter of 2.4 mm was inserted to the right side position of tooth 12. This surgery has been successful and the final metal-ceramic crowns were fixed on the implants after six weeks.

Another example for the use of UFG CP Ti in biomedical applications is in trauma cases, plates (Fig. 23a) and screws (Fig. 23b), which are planned to be widely used for fixing bones. Very high compressive and bending strength and sufficient ductility are the required properties for these plates. Besides, a special conic screw (Fig. 23c) and a unique device for the correction and fixation of spinal column (Fig. 23d), with high static and fatigue strength have been successfully fabricated from UFG Ti by ECAP.

5.3. UFG materials for sport applications

In the sport facilities, particularly where the high strength to weight ratio is need, UFG materials can play an important role. Bulk nanostructured metallic materials could find applications in different fields such as golf, tennis, bicycling, scuba diving, archery, back packing, rock climbing and more. Some of the examples are nanodynamics high performance (NDMX) golf balls, Metallix and Airflow racquets (PowerMetal Technologies and HEAD) [253]. However, none of the products are made by SPD methods. The hollow nanostructured titanium core of the NDMX golf balls is manufactured using the UFG chip machining technology licensed by Purdue University and the Metallix racquets have been made by carbon fibers and Integran'selectro deposition technology. Therefore, it seems that using SPD in sport industry needs more effort from the researchers in this field to find new application for SPD products in sport utilities and to present the great potential of the UFG products in the fabrication of light, strong and long life parts.

5.4. SPD-processed materials for Hydrogen Storage

It was well documented that SPD processing can lead to substantial improvements in the kinetics of hydrogen storage in metallic materials particularly in Mg-based alloys. Most of studies in Hydrogen storage are focused on the methods to use H_2 as lightweight, compact energy carrier for mobile applications. Various approaches have been used to store hydrogen including high pressures, cryogenics, and chemical compounds in which hydrogen is released upon heating. The light weight and low cost of Mg alloys for hydrogen storage made them an attractive choice for on-board mobile applications [271]. However, high thermodynamic stability, high hydrogen desorption temperature and relatively poor hydrogen absorption–desorption kinetics of Mg alloys are big challenges in this regard [20,248]. One way to improve the hydrogen storage properties of Mg-alloys is grain refinement. Skripnyuk et al. [272] in 2004, are the first researchers who study the effect of SPD on the hydrogen storage properties of Mg alloy hydrides using ECAP. They showed that the UFG Mg alloy ZK60 achieved after 8 passes of ECAP by rout A at 250 °C and 300 °C and one additional pass at environmental temperature has a higher hydrogen storage property in means of the hydrogen capacity and the pressure hysteresis in comparison with its CG counterpart. The exact mechanism for grain size that affects Mg hydride's hydrogen storage property still remains unexplained. So far, it is generally documented that the finer grain size, the larger the surface area, which in turn leads to the easier diffusion of dissociated H atoms into the Mg matrix [273]. Furthermore, ECAP processed materials can contain a large fraction of high-angle grain boundaries. The impact of grain boundary on hydrogenation kinetics has been intensively studied. Reports showed that hydrogen could diffuse much faster along the grain boundaries. Besides, the ECAP process generates defects such as vacancies and dislocations which produce a constructive effect on the diffusion kinetics. Many details of the effect of different parameters on the hydrogen storage of ECAP processed Mg-alloys and the mechanisms involved in this phenomenon can be found in the recent critical review paper of Wang et al. [273]. In some other studies, the effect of HPT on the hydrogen storage properties of Mg ZK60 [274] and Mg_2Ni have been investigated. In general, HPT enhanced the hydrogen sorption kinetics due to a high density of planar lattice defects, such as crystallite boundaries and stacking faults, induced by HPT [248,20]. It is reasonable to conclude that SPD processes in general and HPT and ECAP processes in particular have the great potential to be used in the production of the nanocrystalline elements. ECAP can cheaply use for the fabrication of cylindrical hydrogen batteries while HPT could be used for the construction of metal hybrid tablets. Moreover, the applicability of the use of other methods like TE and SSE that have a great potential for commercialization, and are cheaper and easier than the other methods, would be of great interest in this field.

6. Summery and conclusions

During the last three decades, severe plastic deformation has progressed as a novel method to achieve nano/ultra-fine grained structure in a wide range of metallic materials. To the end of 2016, SPD processing has attracted the significant attention of more than 4700 researchers from 69 countries. The bulk of the work is based on the characterization of microstructure and mechanical properties of SPD processed materials. The microstructural characterization mainly focuses on the study of grain size, examination of the grain boundary and dislocation structure and the texture evaluation. In spite of being three decades old and the extensive works on microstructure and mechanical properties, SPD constitutes a field, which is still young and demands considerable challenges. The reason can be explained by several points of view. First, compared with common aspects of SPD processed materials, several features such as magnetic properties, weldability and powder consolidation have attracted less attention. Second, the achievements in some aspects of SPD processed materials such as wear behavior; corrosion resistance and the simultaneous increase in the strength and ductility are contradictory and still need further investigations. Third, limited efforts have been directed toward production of materials other than metallic alloys by SPD process. Although extensive works have been done to produce composite materials by ARB, the fabrication of composites as well as hard to deform materials, polymers and ceramics (at low or moderate temperature) by various SPD methods is still a challenge. Finally, it is worth nothing that up to now, more than 90% of the publications in this field comprises just three conventional SPD methods including ECAP, HPT and ARB. However, about 120 methods with different deformation modes and different shapes/geometries including rods, bars, billets, tubes and sheets have been introduced as new SPD processes. Among many types of conventional and new SPD techniques, the efforts to scale up and commercialization have focused on the ECAP process. Therefore, the practical applications of SPD processed materials demands the commercialization of other SPD methods and requires further investigations in the future.

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Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

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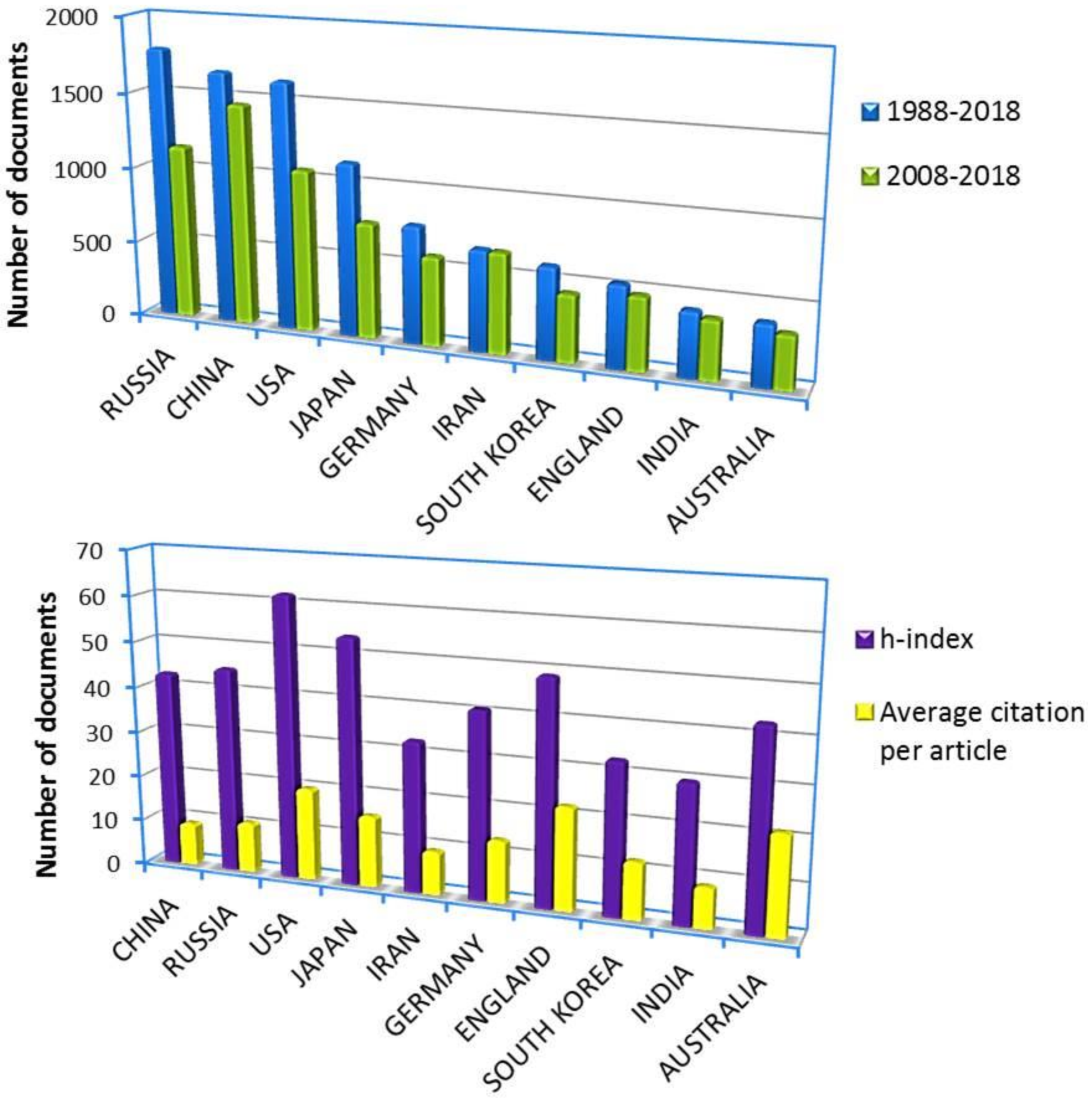


Fig. 1. Rank of the countries according to (a) the total number of publications in the field of SPD, and (b) the citations to the published articles during 2008-2018 based on different criteria

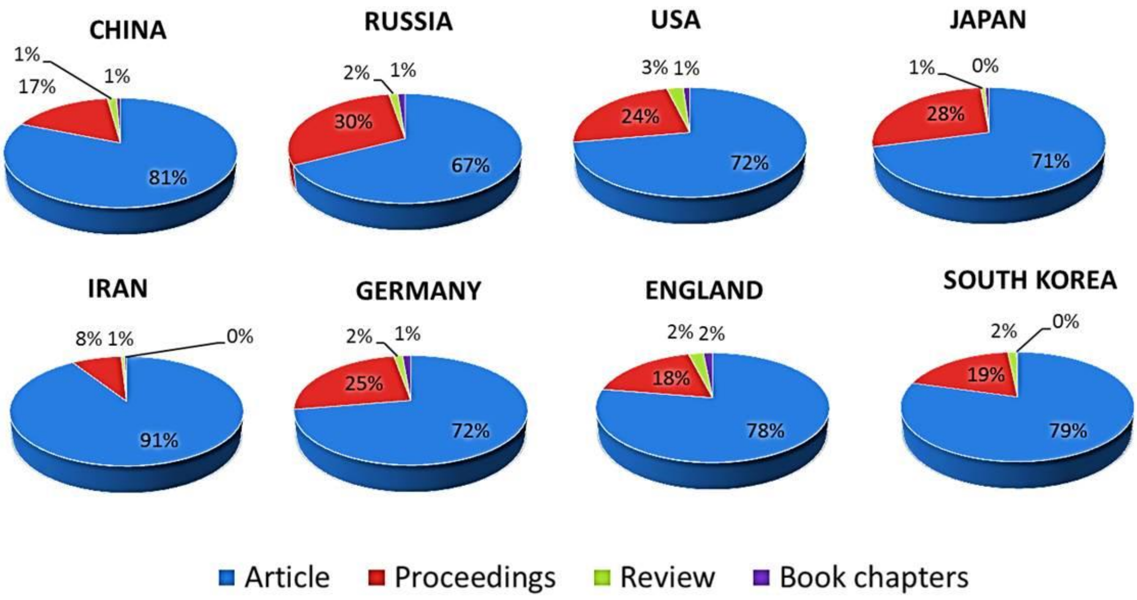


Fig. 2. Fraction of various types of published documents for the most important countries in field of SPD

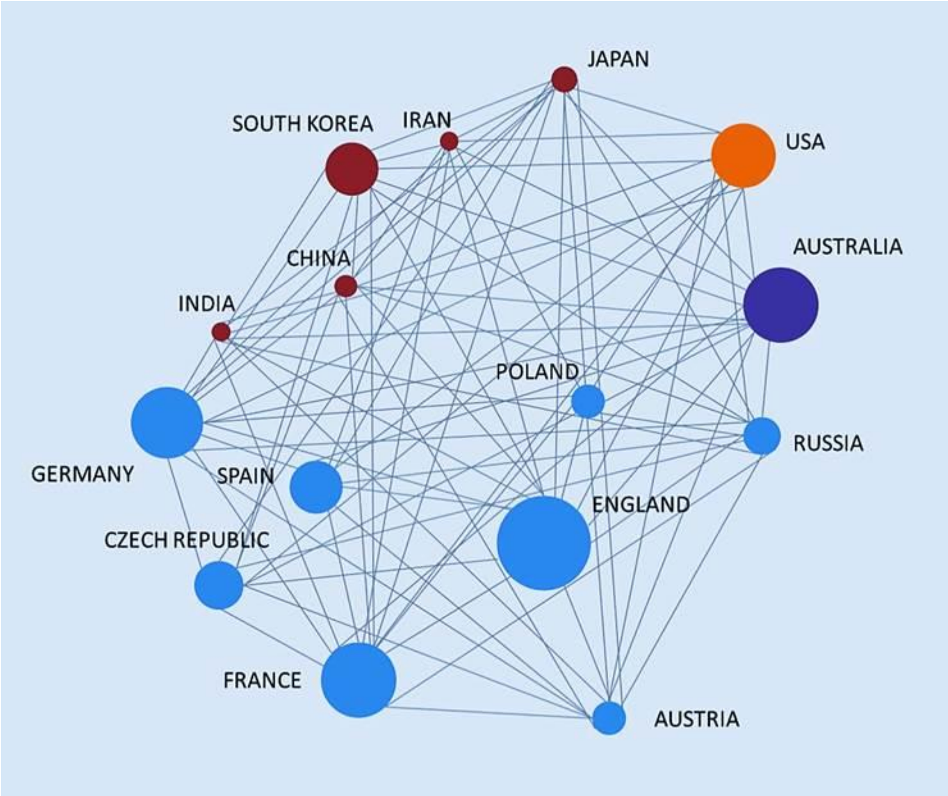


Fig. 3. Collaboration of various countries in the field of SPD up to the beginning of 2016 for the top-ranked countries in the field of SPD; the countries are specified by circles and their collaborations are denoted by the solid lines. The larger the number of articles published in collaboration with scientists from other nations, the larger the circle

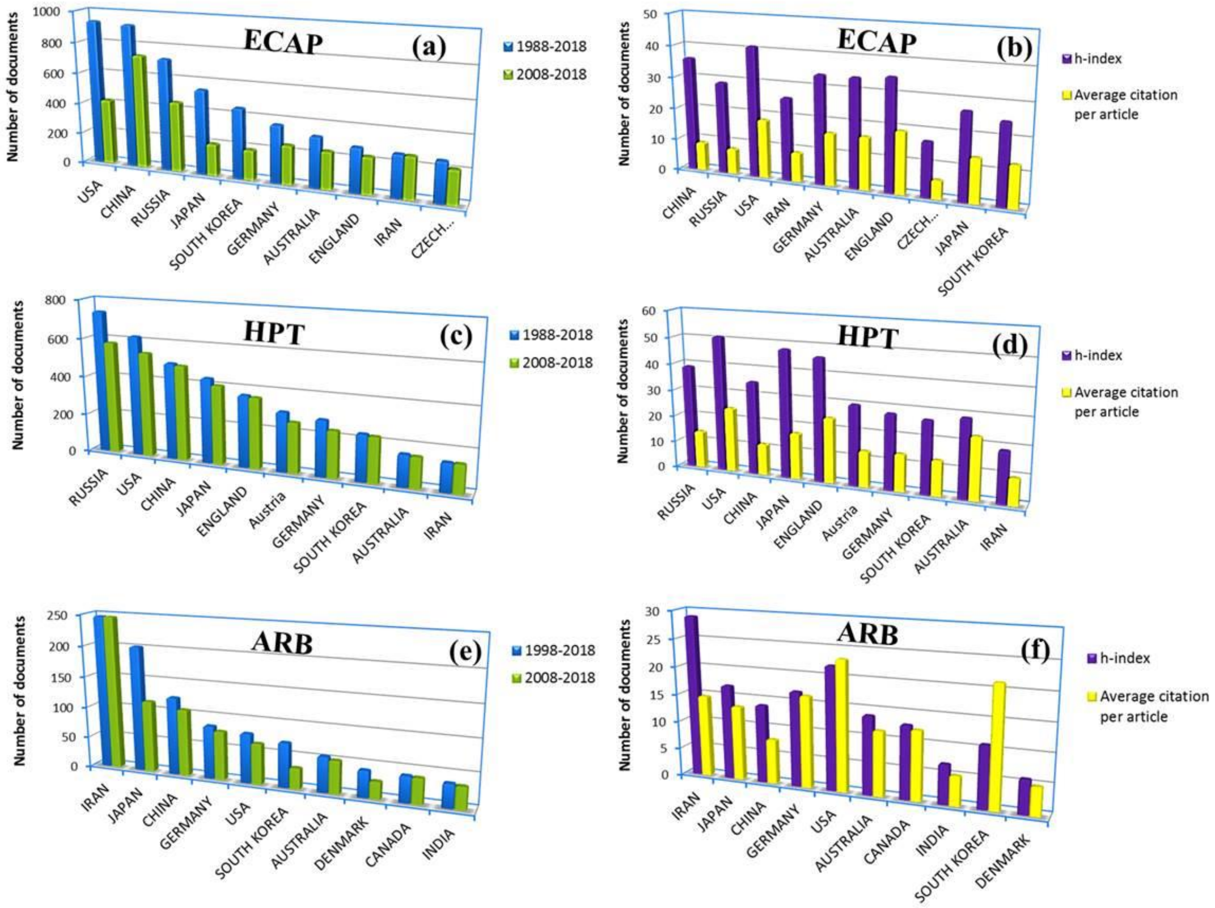


Fig. 4. Rank of the countries in the fields of (a, b) ECAP, (c, d) HPT, and (e, f) ARB, according to (a, c, e) the total number of publications in the field of SPD, and (b, d, f) the citations to the published articles during 2008-2018 based on different criteria

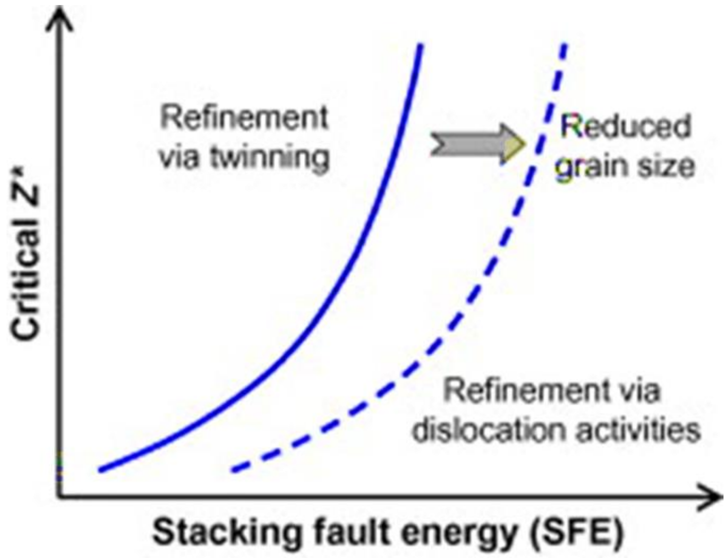


Fig. 5. Effect of the SFE and grain size on the dominating structural refinement mechanism [31]

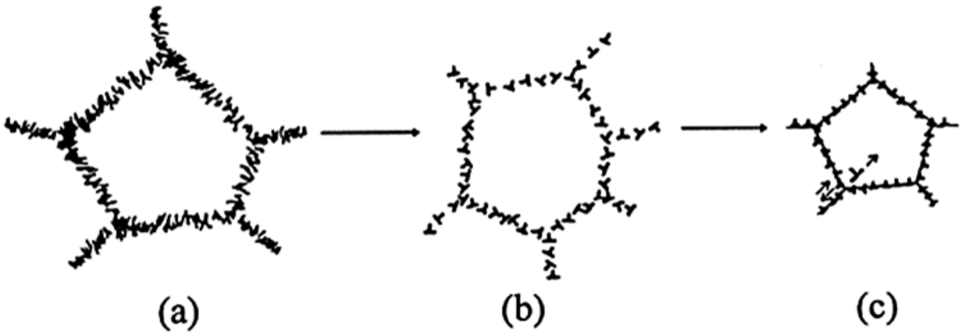


Fig. 6. The proposed model for dislocation substructure at different stages of SPD [1]

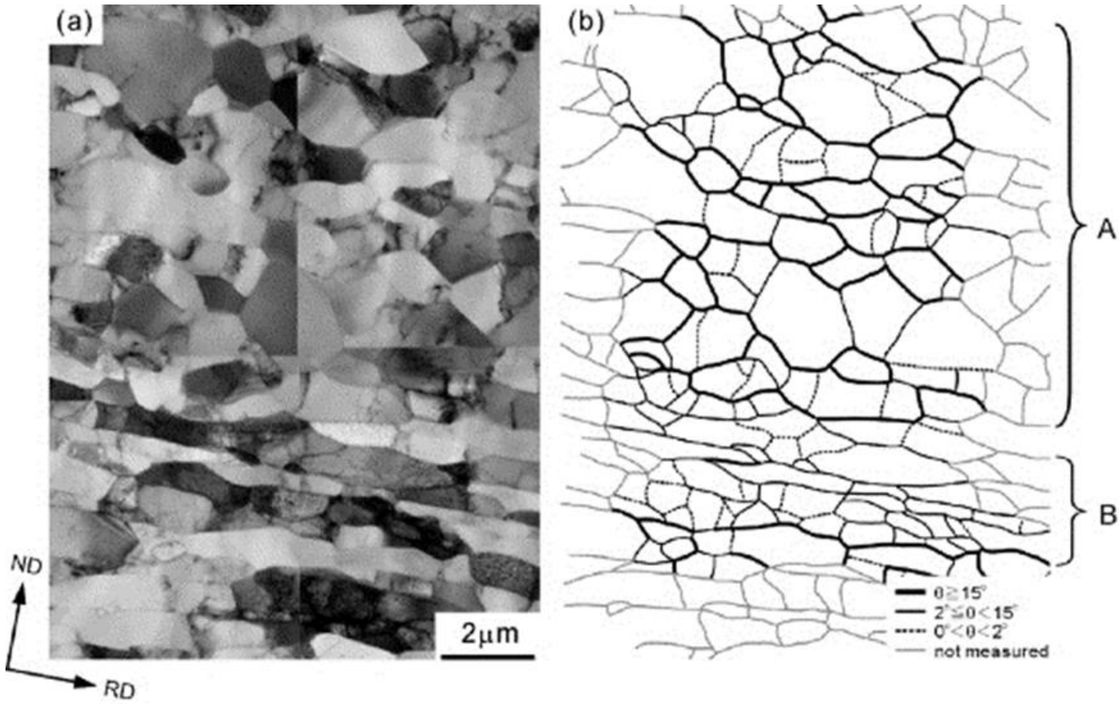


Fig. 7. (a) TEM microstructure and (b) the corresponding grain boundary map of pure Al after six ARB cycles [39]

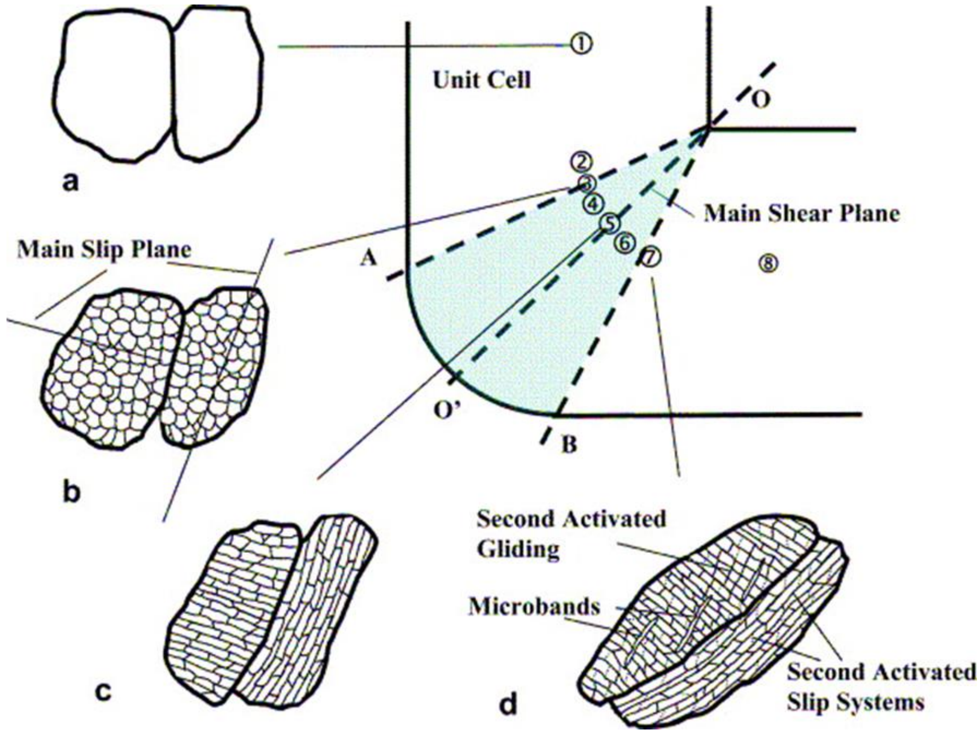


Fig. 8. The process of microstructural evolution during the first pass of ECAP: (a) the initial coarse grains under the shear stress, (b) dislocation generation and construction of dislocation cells (c) self-organized alignment of dislocation walls along slip planes by dislocation gliding and (d) segmentation through secondary slip and microbands [40]

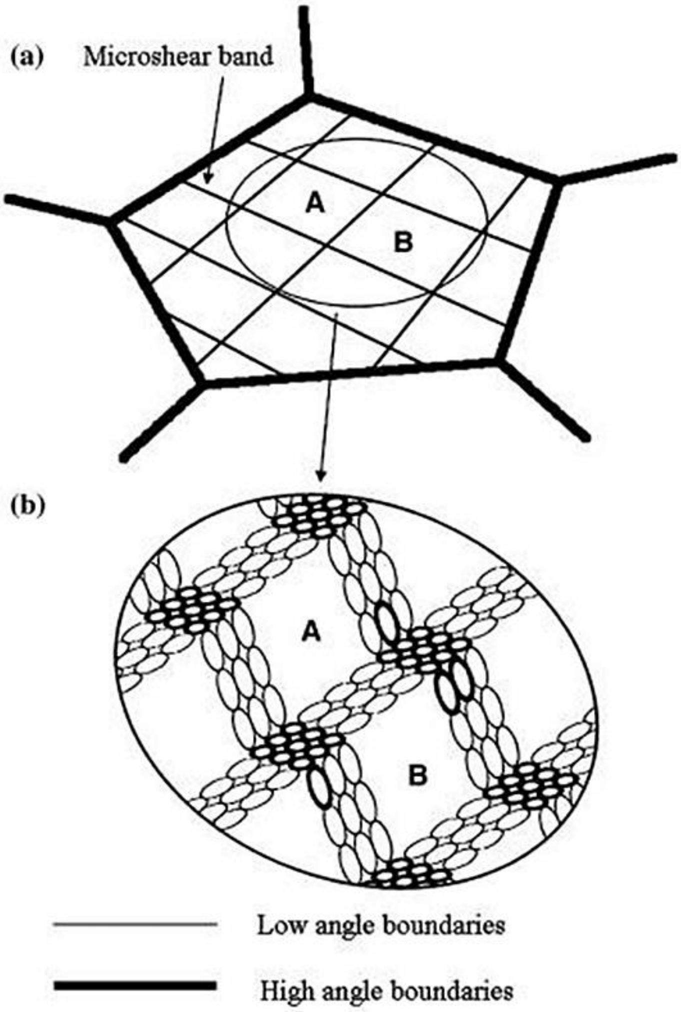


Fig. 9. Schematic illustration of the formation of (a) microshear bands at low strains and (b) subsequent formation of new grains at the intersections and along the microshear bands at large strains [42]

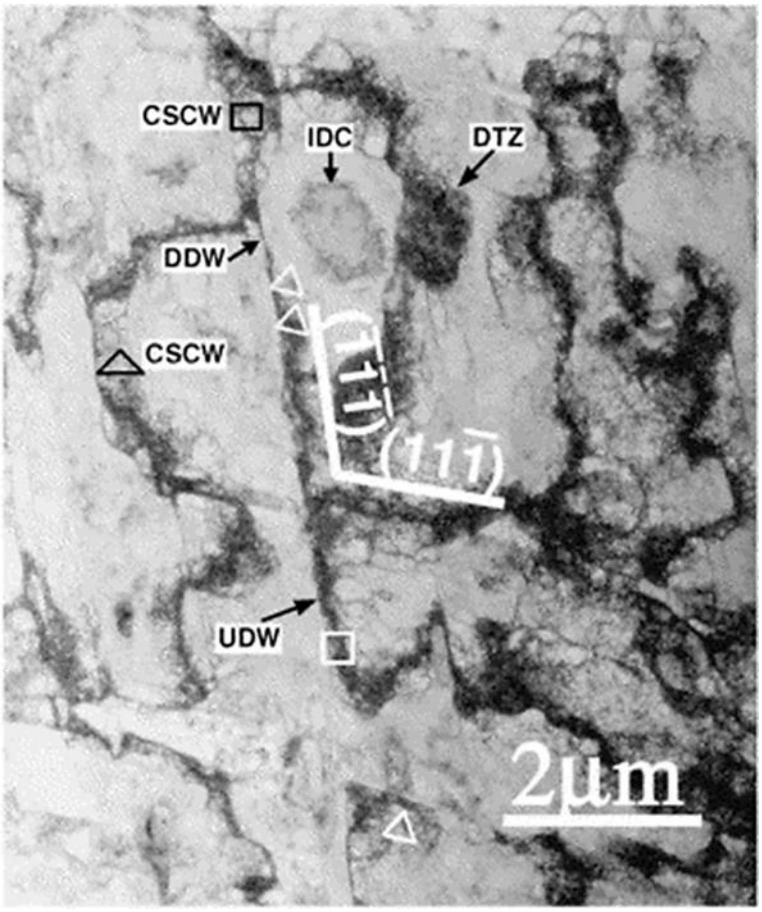


Fig. 10. TEM micrograph showing the different dislocation structures including cells, IDC, CBs, CSCWs, DDWs, UDWs and DTZs [35]

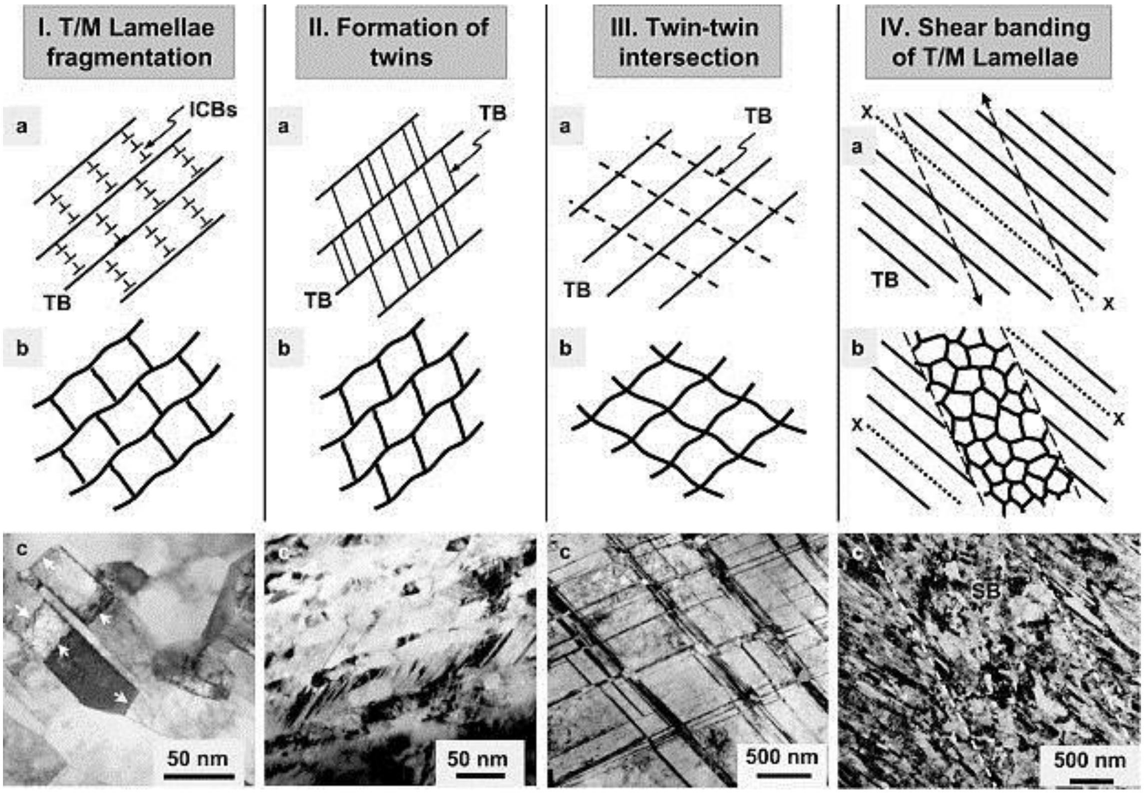


Fig. 11. Schematic illustrations showing four mechanisms of twinning-based grain refinement and the corresponding TEM images [31]

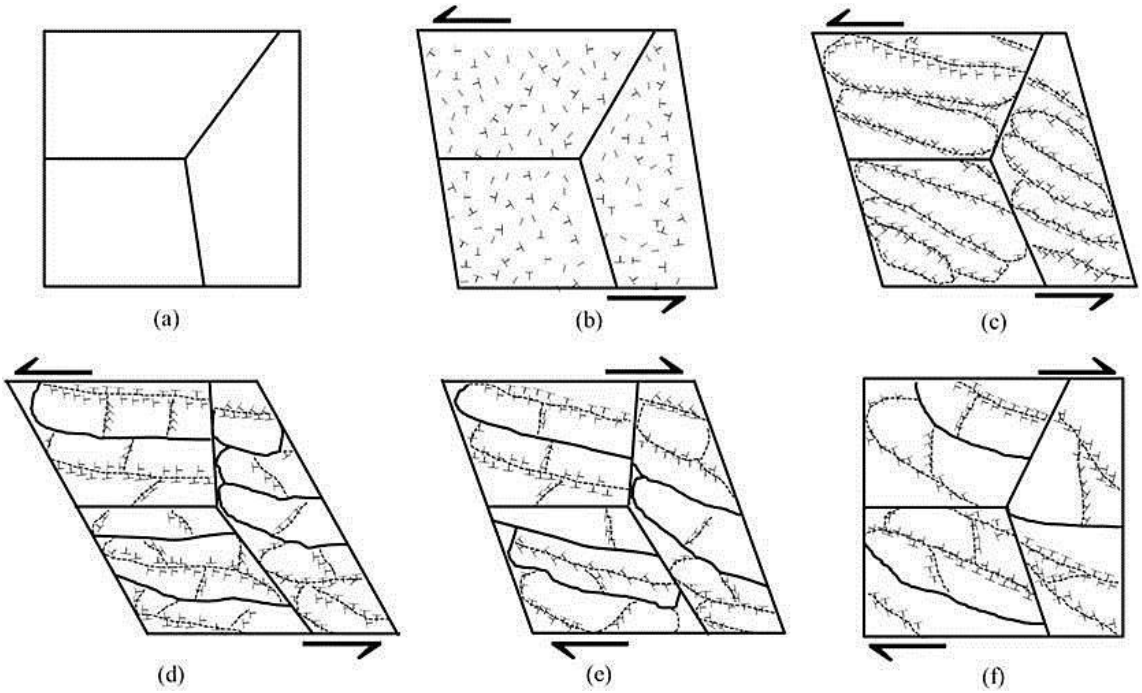


Fig. 12. Schematic illustration of the microstructural evolution during the SPD process that contains forward shear (a-d) and the shear strain reversal (e-f): (a) Initial cell structure, (b) homogeneous distribution of dislocations, (c) elongated cell formation, (d) dislocations blocked by subgrain boundaries and break up of elongated subgrains, (e) diminishing of the misorientation angle and/or eliminating of the dislocation boundaries and (f) final microstructure [54]

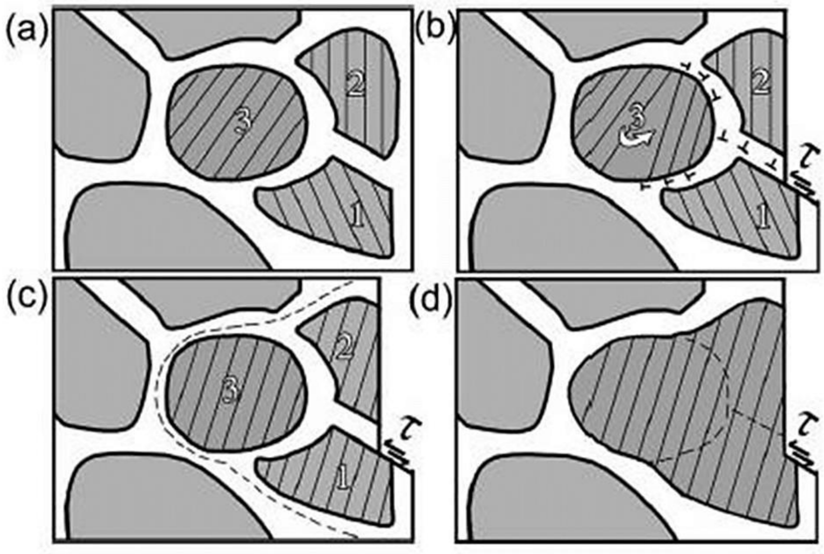


Fig. 13. Schematic illustration of a grain growth model via grain boundary sliding and grain rotation: (a) nano grains with high-angle grain boundaries before plastic deformation, (b) shear of grains 1 and 2 by gliding grain boundary dislocations and subsequent occurrence of rotation of grain 3 by climbing grain boundary dislocations, (c) multiple grain rotations leading to grain agglomeration and (d) A large grain formed with subgrain boundaries (highlighted by dotted line) due to incomplete grain coalescence [70]

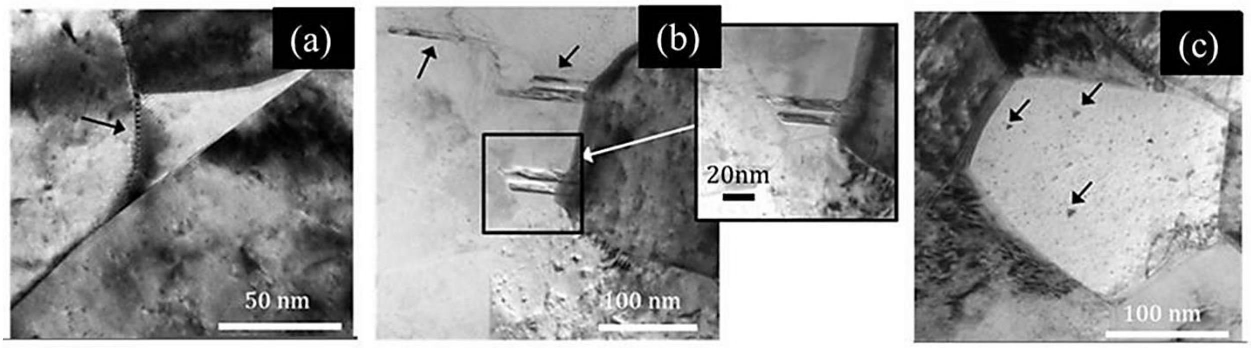


Fig. 14. Microstructural investigations of grain growth in Cu after 12 passes of SSE; (a) Moiré (b) deformation twins and (c) distinct stacking fault tetrahedra (SFT) [56]

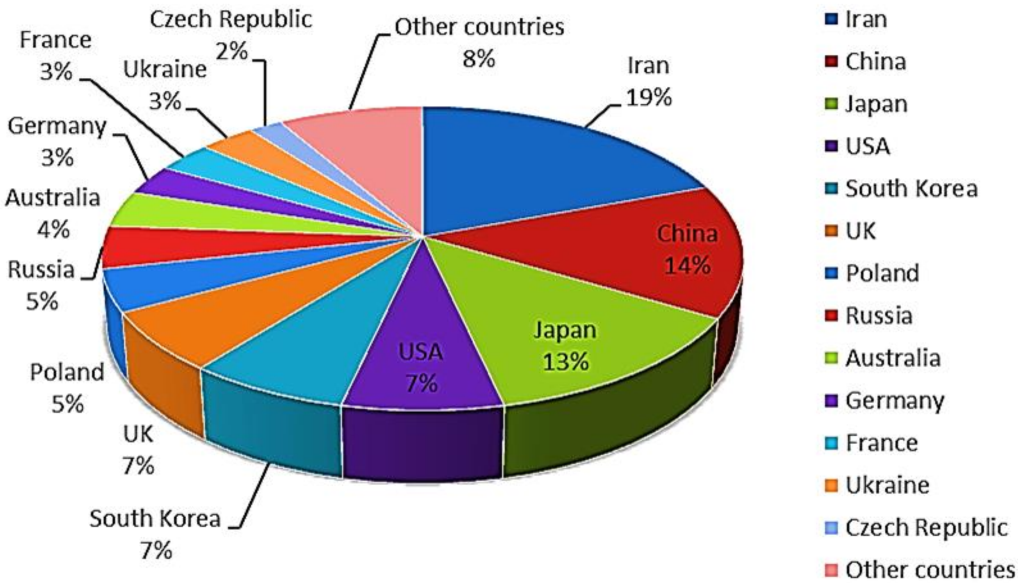
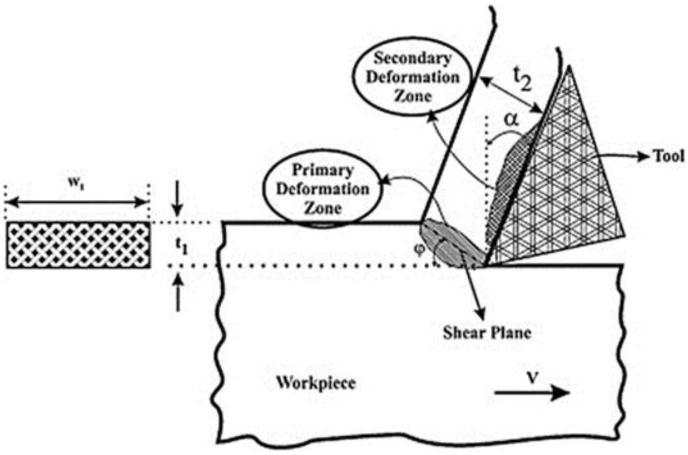
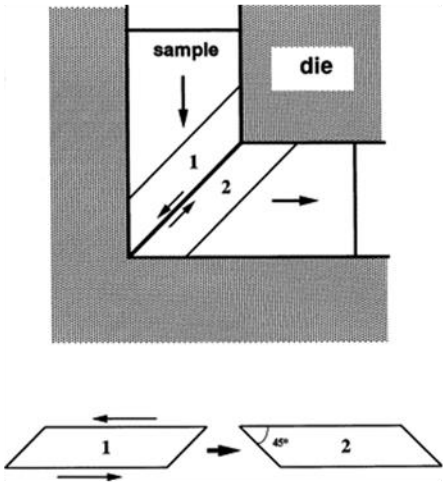


Fig. 15. Contribution of the countries to the introduction of new SPD techniques



(a)



(b)

Fig. 16. Shear plane in the process of (a) "large strain machining" [79], and (b) ECAP [80]

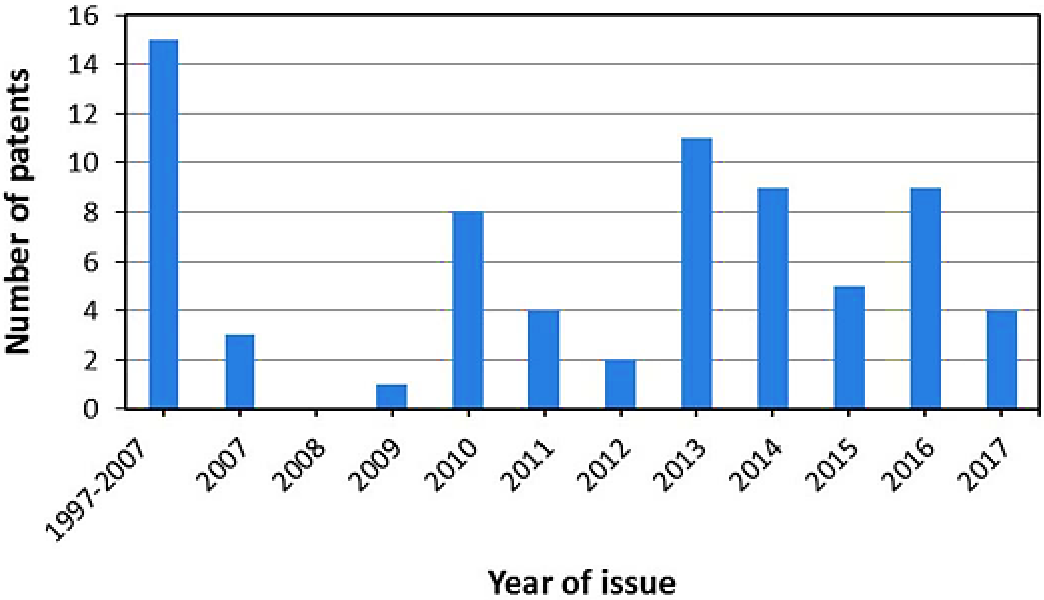


Fig. 17. Number of the patents corresponding to the SPD field in each year

Fig. 18. ECAP die with 4000 tones press capacity [252]

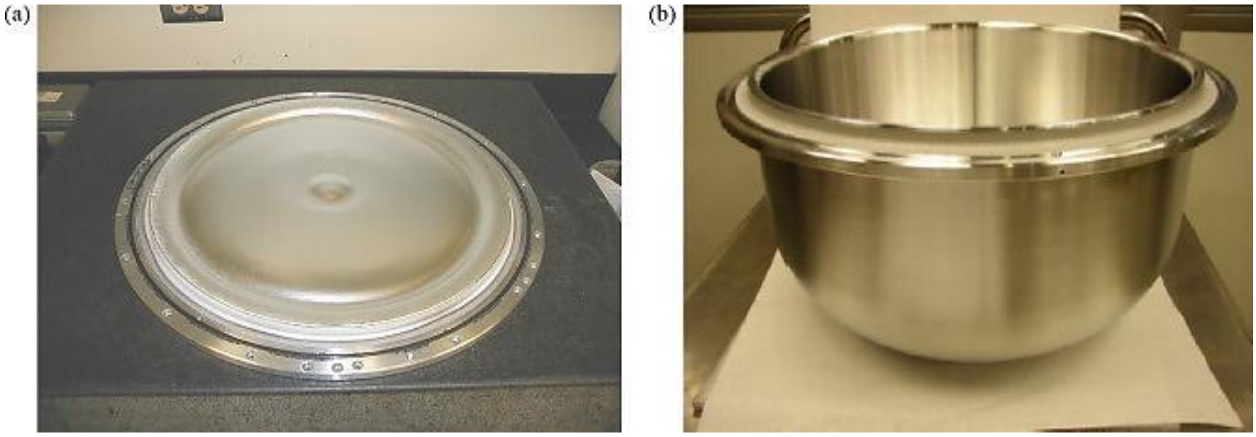


Fig. 19. Flat 300 mm monolithic ECAE Al0.5Cu target with AMAT design and overall dimensions diameter 523.8 mm × 25.4 mm thickness sputtered up to 2738 kWh (+52% life increase) and (b) non-flat and non-sputtered 300 mm monolithic ECAE 6N Cu with HCM Novellus design and overall dimensions diameter 393.7 mm × 25.4 mm thickness × 381 mm height [252]

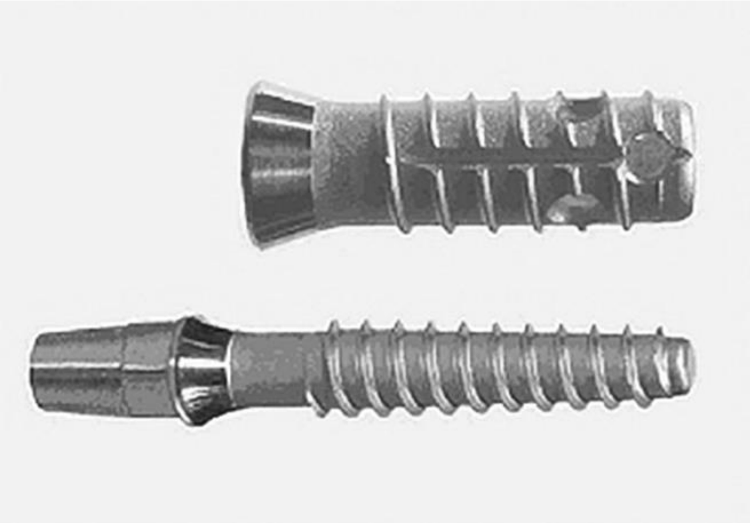


Fig. 20. A 5 mm diameter Timplant (above) and 2.4 mm diameter Nanoimplant (below) [268]

Fig. 21. View of ultrafine-grained billets with a diameter of 7 and a length of 300 mm from commercially pure grade titanium [269]

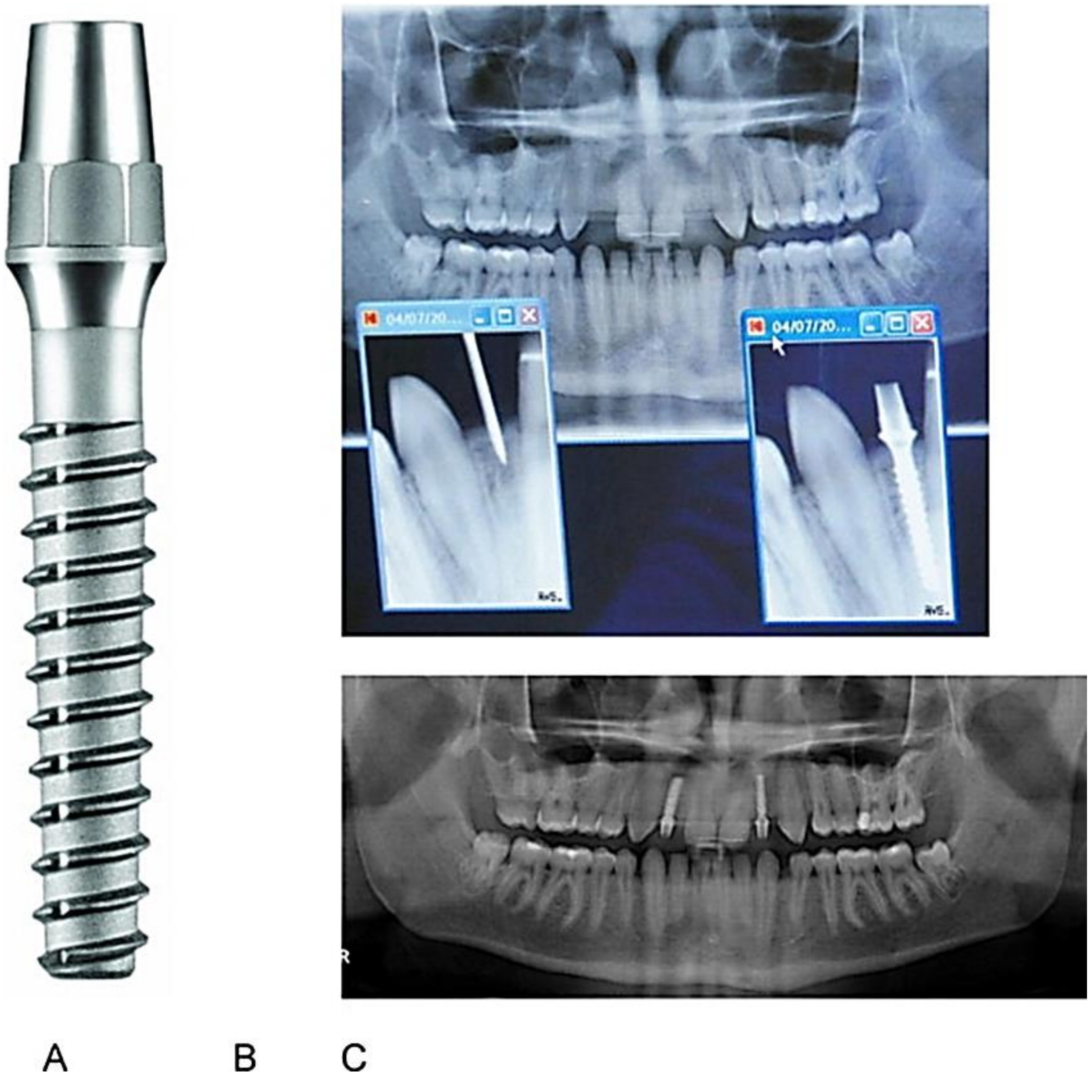


Fig. 22. (a) Implant from nanostructured Ti and (b) and (c) X-ray photos after surgery and control photo after incorporation of implants [256]

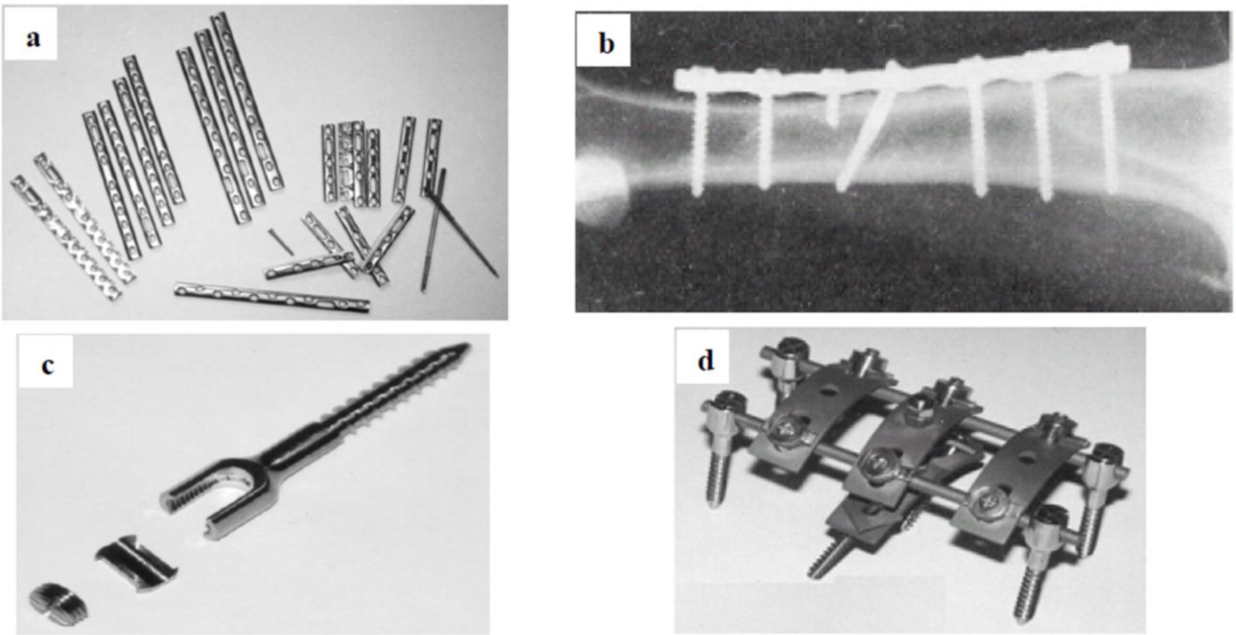
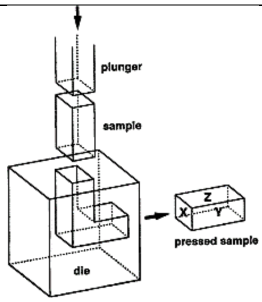
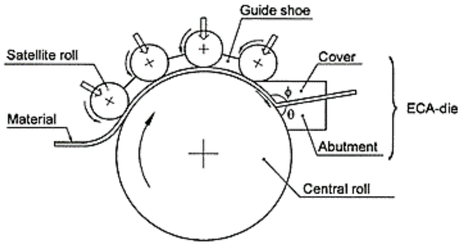
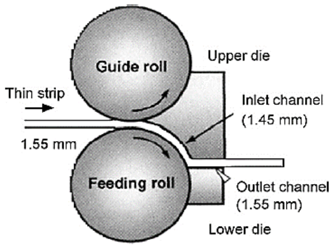
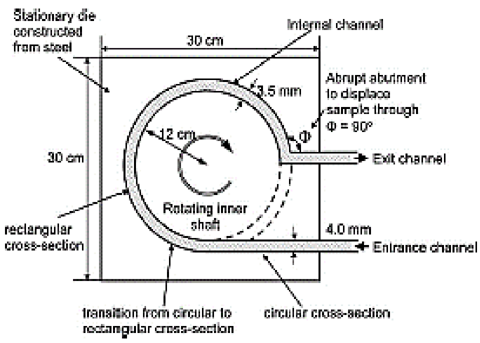
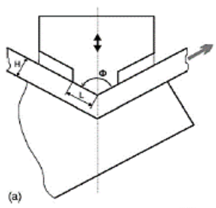
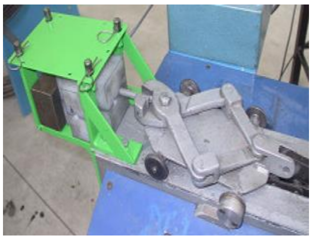
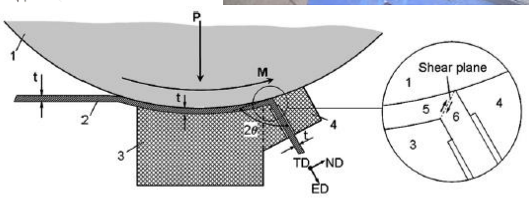


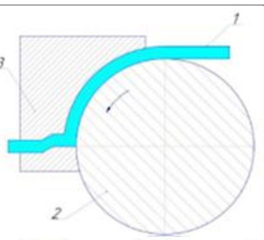
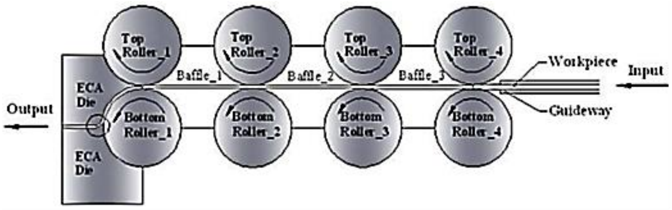
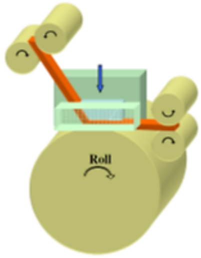
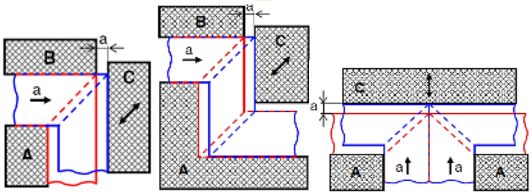
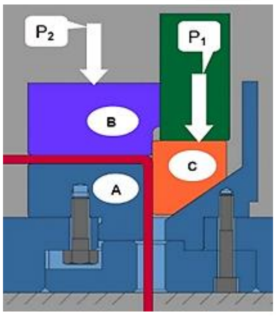
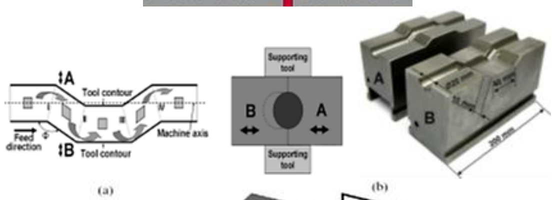
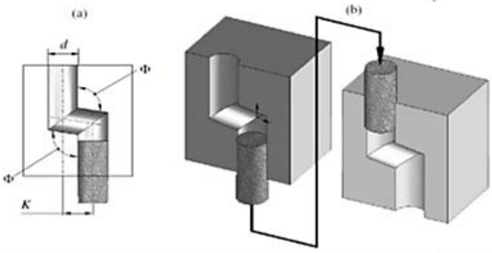
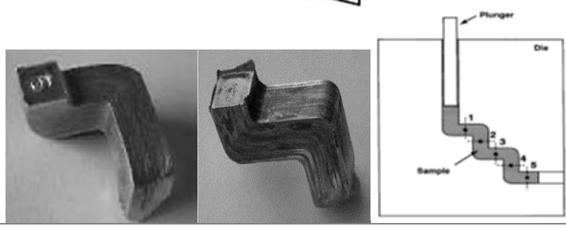
Fig. 23. Medical implants made of nanostructured titanium: (a) and (b) plate implants for osteosynthesis, (c) conic screw for spine fixation and (d) device for correction and fixation of spinal column [270]

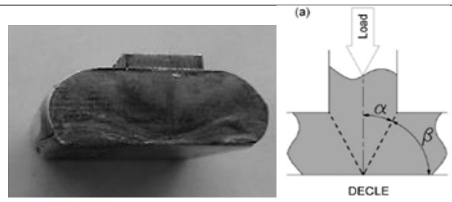
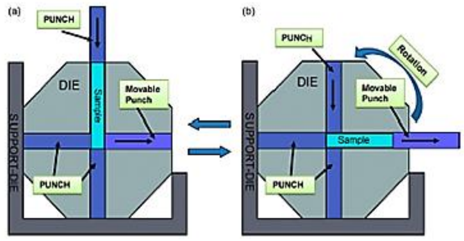
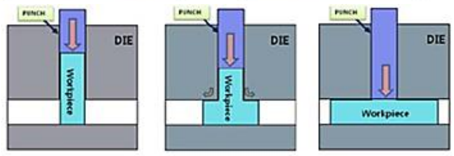
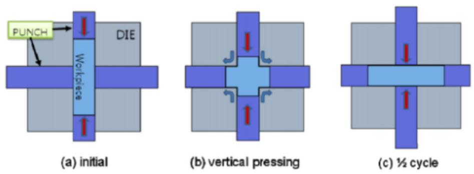
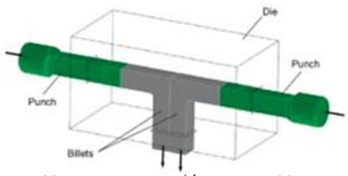
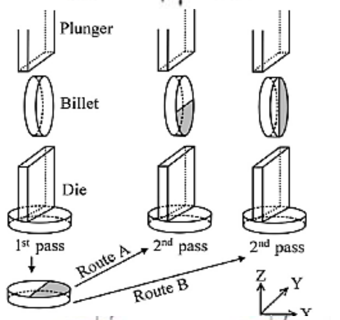
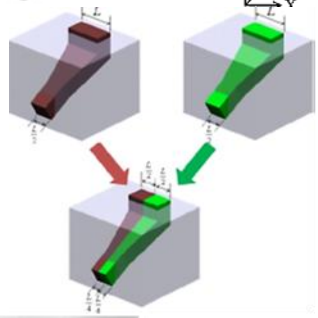
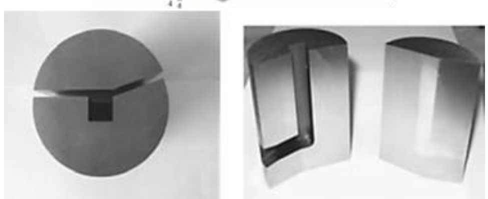
Table 1. Summary of the Contribution of the countries in the different categories of SPD techniques

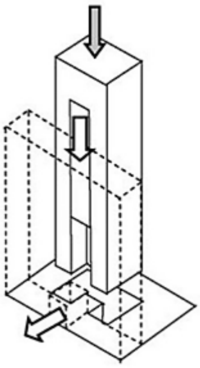
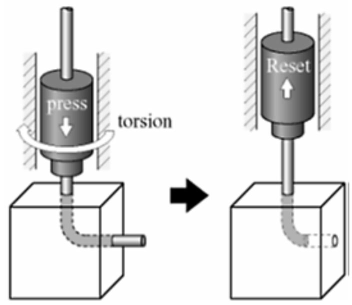
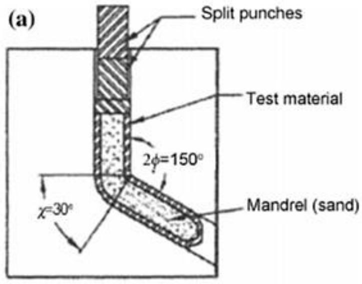
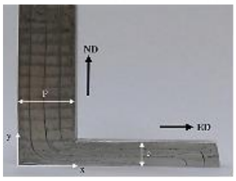
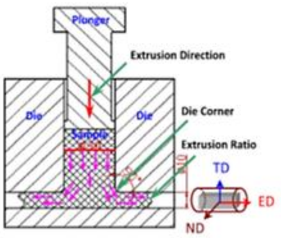
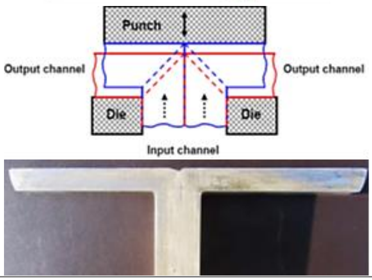
	Based on ECAP	Based on torsion/shear under high pressure	Based on direct/indirect extrusion	Based on pressing/ forging	Based on rolling	Combined techniques	Total
Iran	4	1	8	4	2	11	30
China	4	2	8	3	1	4	22
Japan	5	6	3	-	3	3	20
USA	4	2	-	2	1	2	11
South Korea	6	2	1	1	-	1	11
UK	5	3	-	-	-	2	10
Poland	4	-	1	1	-	1	7
Russia	4	-	1	1	-	1	7
Australia	2	3	1	-	-	-	6
Germany	1	-	3	-	-	1	5
France	1	2	1	-	-	1	5
Ukraine	-	-	4	-	-	1	5
Czech Republic	1	-	-	-	-	2	3
India	2	-	-	-	-	-	2
Belgium	1	-	1	-	-	-	2
Spain	1	-	-	-	-	-	1
Austria	-	1	-	-	-	1	2
Taiwan	1	-	-	-	-	-	1
Norway	-	-	1	-	-	-	1
Canada	-	-	-	1	-	-	1

Table 2. Summary of different SPD techniques based on ECAP

	SPD technique	Illustration	[Ref.]
1	Equal-channel angular pressing (ECAP)		[81]
2	Conshearing process		[82]
3	Continuous confined strip shearing (C2S2)		[83-86]
4	ECAP–Conform		[87]
5	Equal channel angular drawing (ECAD)	 	[88,89]
6	Continuous frictional angular extrusion		[90]

7	Multi ECAP Conform		**[91]**
8	Integrated conventional tandem rolling with ECA deformation (CR-ECA)		[92]
9	Single roll drive equal channel angular process		[93]
10	Single/two turn incremental ECAP (I-ECAP); double billet I-ECAP		[94,95]
10	Incremental ECAP of plates		[96]
12	Equal channel angular swaging		[97]
13	Equal-channel angular pressing in parallel channels		[98]
14	Multi turn/pass ECAP (3D ECAP)		[99,100,80]

15	Dual equal channel lateral extrusion (DECLE)		[101]
16	Rotary-fie equal channel angular pressing		[102,103]
17	T-shaped equal channel angular pressing		[104,105]
18	Cross-equal channel angular pressing (firstly named as cross-channel extrusion)		[106,107]
19	ECAP with converging billets		[108]
20	Repetitive upsetting		[109]
21	Half channel angular extrusion (HCAE)		[110]
22	ECAP (New design1)		[111]

23	ECAP (New design2)		[112]
24	Modified ECAP		[113]
25	ECAP for processing of tubular samples		[114,115]
26	Non-equal channel angular pressing / channel angular deformation (CAD)		[116,117]
27	Double change channel angular pressing		[118]
28	Incremental Angular Splitting		[119]

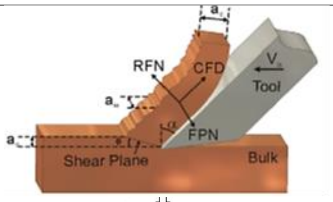
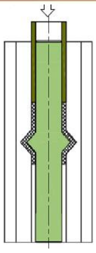
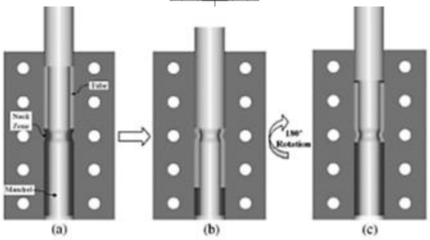
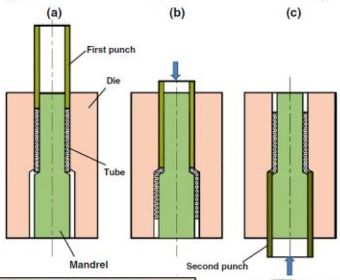
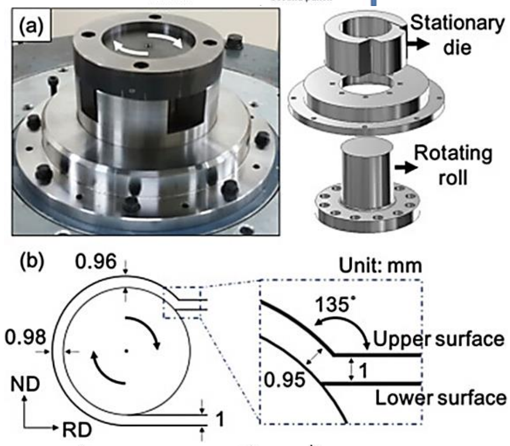
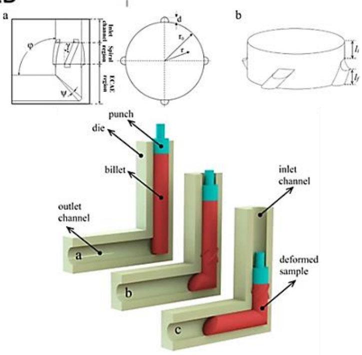
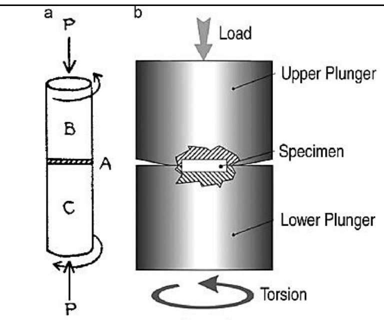
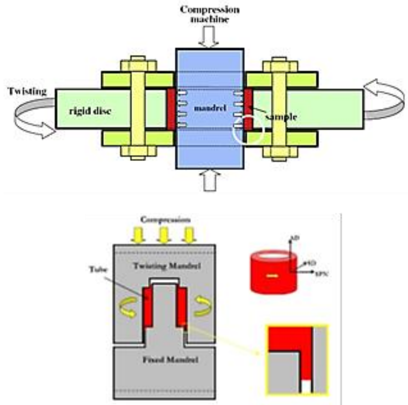
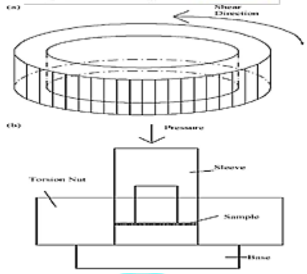
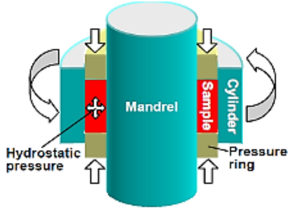
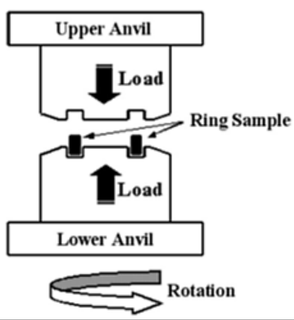
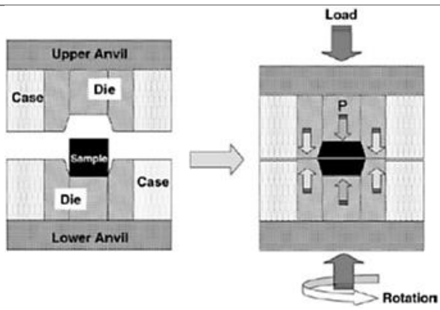
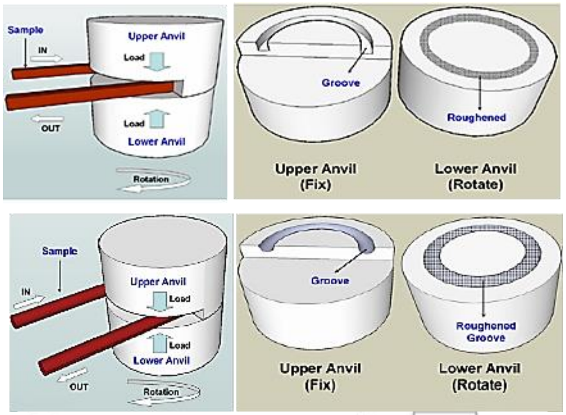
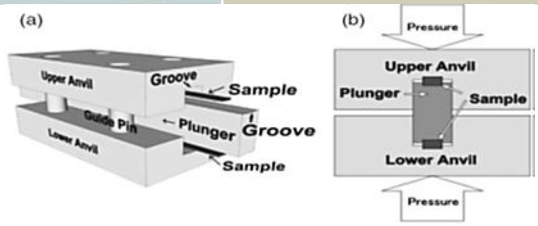
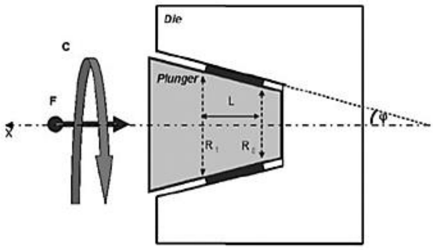
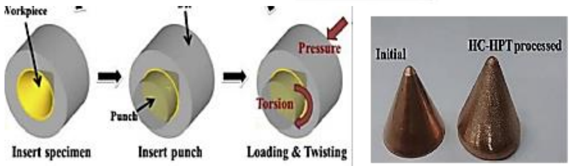
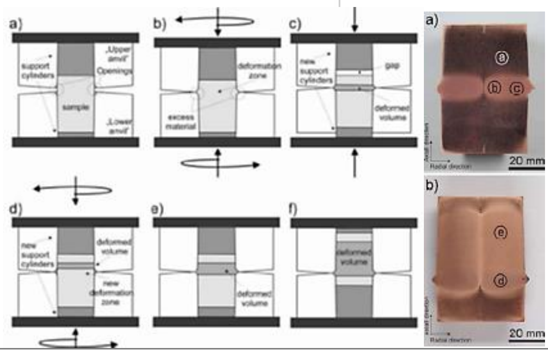
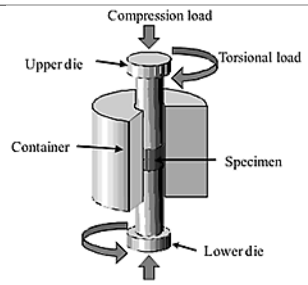
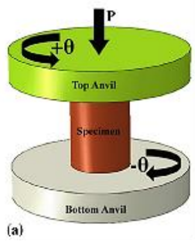
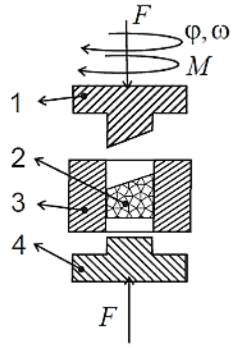
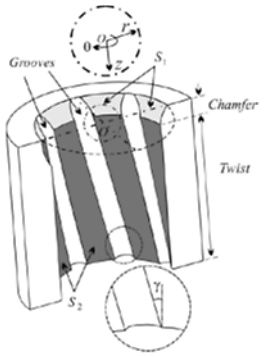
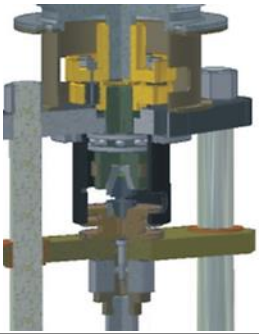
29	Large strain machining		[120,79]
30	Tubular channel angular pressing (TCAP)		[121]
31	Tube channel pressing (TCP)		[122,123]
32	Parallel tubular channel angular pressing (PTCAP)		[124]
33	Single-roll angular-rolling (SRAR)		[125]
34	Spiral equal channel angular extrusion (Sp-ECAE)		[126]

Table 3. Summary of different SPD techniques based on application of torsion/shear (under high pressure)

	SPD technique	Illustration	[Ref.]
1	High-pressure torsion (HPT)		[13,127]
2	High pressure tube twisting (HPTT)		[128,129]
3	Rotation torsion		[130]
4	High-pressure shearing (t-HPS)		[131]
5	HPT for ring specimens		[132]

6	High pressure torsion for bulk samples		[28]
7	Continuous high-pressure torsion for bars/rods		[29,133]
8	High pressure sliding		[134]
9	Cone-cone method		[135]
10	Hollow cone high-pressure torsion		[136]
11	Incremental high pressure torsion		[137]

<table>
<tr><td>12</td><td>Compressive torsion processing</td><td>
</td><td>[138]</td></tr>
<tr><td>13</td><td>High pressure double torsion (HPDT)</td><td>
</td><td>[139]</td></tr>
<tr><td>14</td><td>High pressure torsion-cylindrical segment (HPT-CS)</td><td>
</td><td>[140]</td></tr>
<tr><td>15</td><td>Axi-symmetric forward spiral extrusion (AFSE)</td><td>
</td><td>[141]</td></tr>
<tr><td>16</td><td>High-speed high pressure torsion (HS-HPT)</td><td></td><td>[142]</td></tr>
</table>

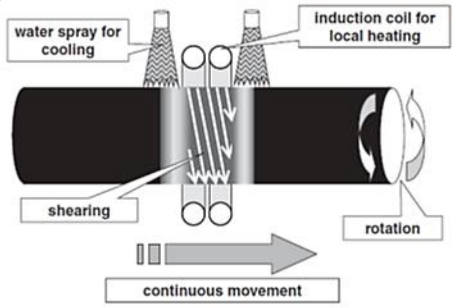
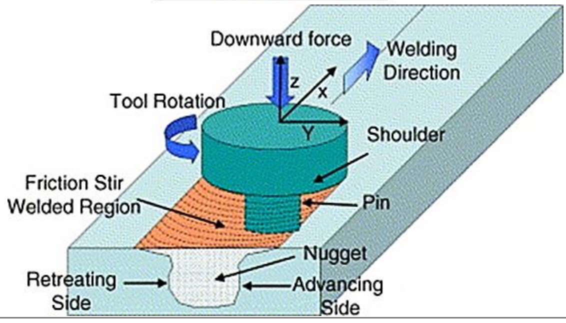
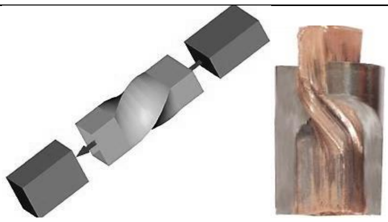
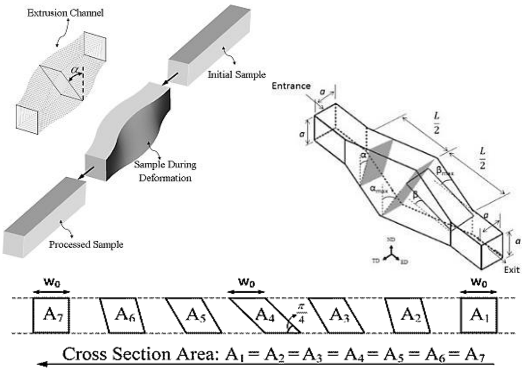
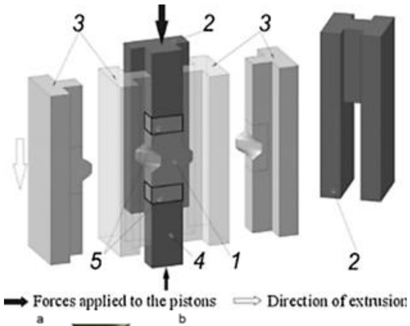
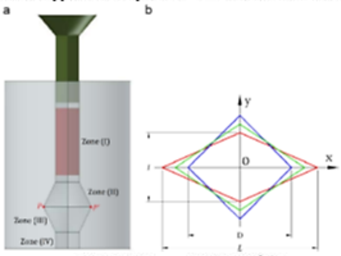
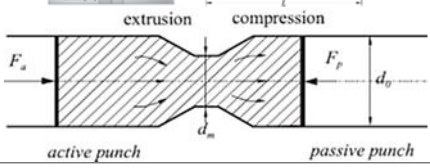
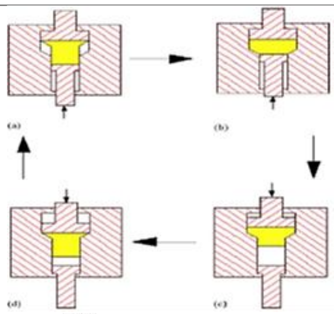
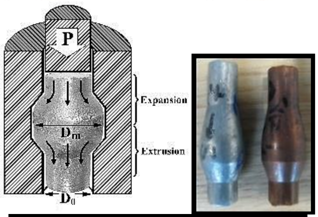
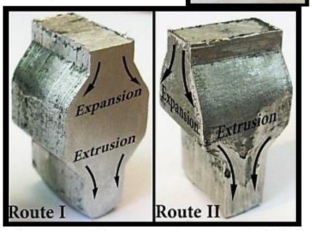
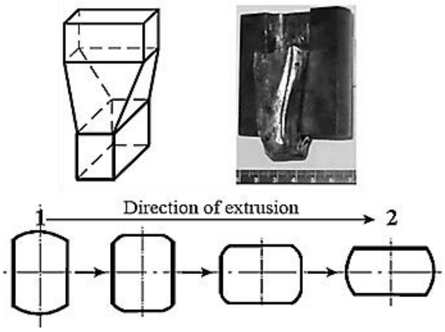
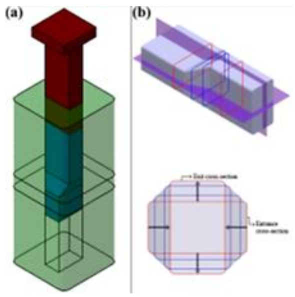
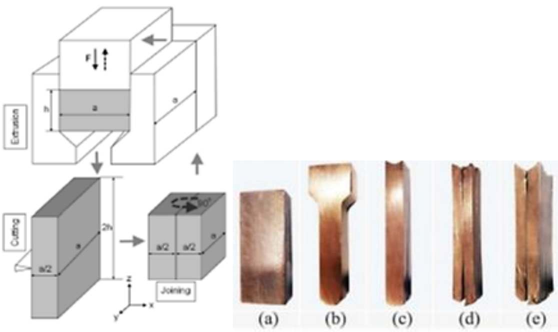
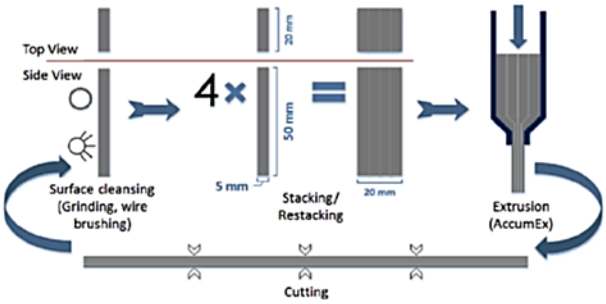
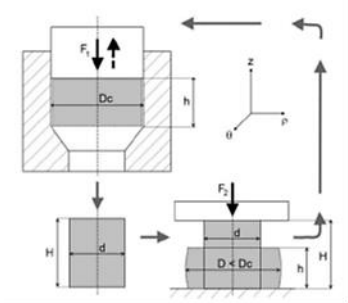
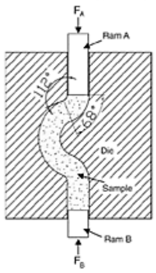
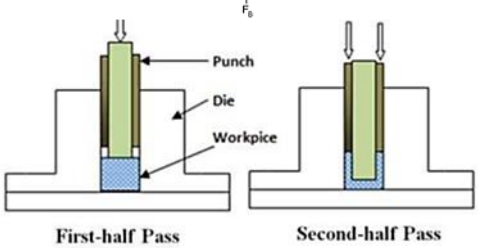
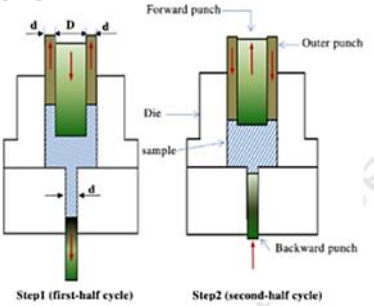
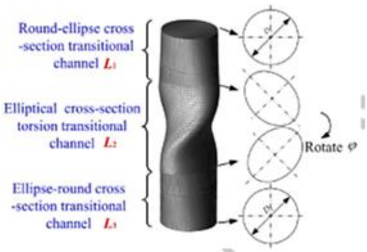
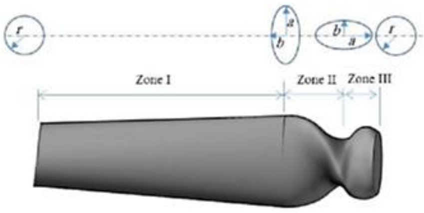
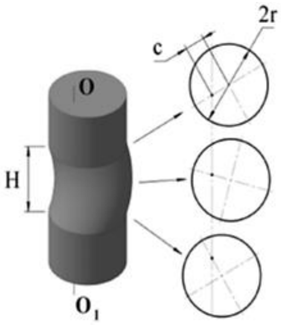
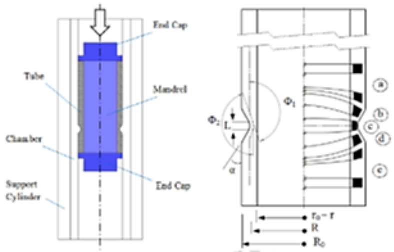
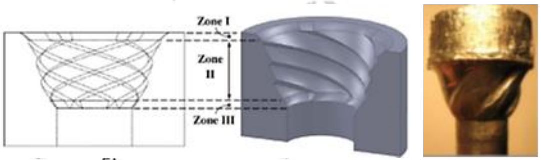
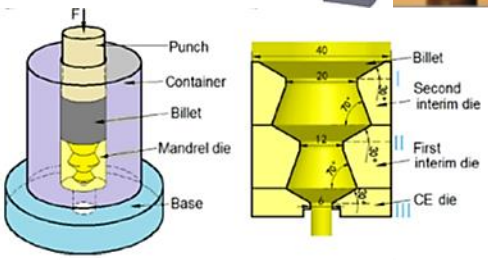
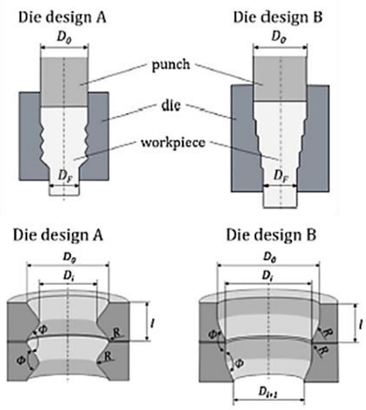
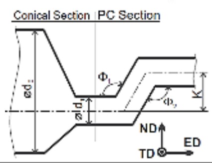
17	Severe torsion straining (STS)		[143]
18	Friction stir processing (FSP)		[144,145]

Table 4. Summary of different SPD techniques based on direct/indirect extrusion

	SPD technique	Illustration	[Ref.]
1	Twist extrusion (TE)		[159-166]
2	Simple shear extrusion (SSE)		[146,148]
3	Planar twist extrusion (PTE) (similar to SSE)		[167]
4	Pure shear Extrusion (PSE)		[168]
5	Cyclic extrusion-compression (CEC)		[169]

6	Repetitive upset extrusion (RUE)		[170-174]
7	Cyclic expansion-extrusion (CEE)		[175,176]
8	Cyclic expansion extrusion (CEE) for rectangular samples		[177]
9	Spread extrusion		[178]
10	Equal channel forward extrusion (ECFE) (similar to spread extrusion)		[179]
11	Multiple direct extrusion		[180]

12	Accumulated extrusion (AccumEx)		[181]
13	Repetitive extrusion and upsetting		[173]
14	C shape equal channel reciprocating extrusion (CECRE)		[182]
15	Accumulative back extrusion (ABE)		[183]
16	Cyclic forward-backward extrusion		[184]
17	Elliptical cross-section spiral equal-channel extrusion (ECSEE)		[185]

18	Nonlinear rotary extrusion (NRE) (similar to ECSEE)		[148]
19	Off-axis twist extrusion		[186]
20	Tube cyclic extrusion-compression (TCEC)		[187]
21	Vortex extrusion (VE)		[188,189]
22	Variable cross-section direct extrusion (CVCDE)		[190,191]
23	Gradiation extrusion		[192,193]
24	Integrated extrusion		[194]

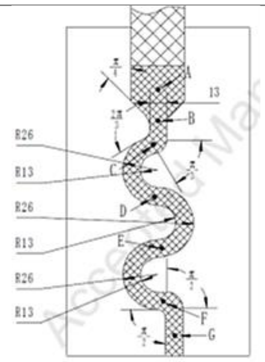
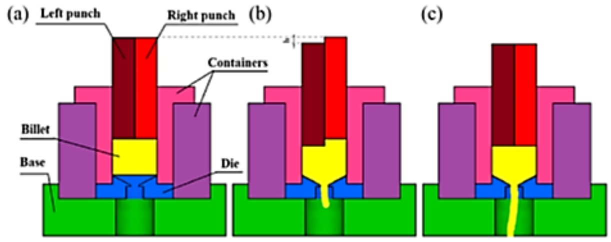
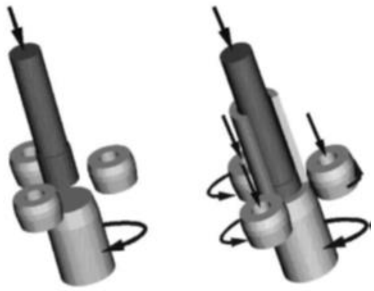
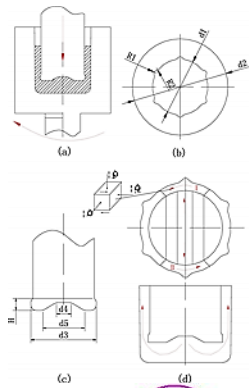
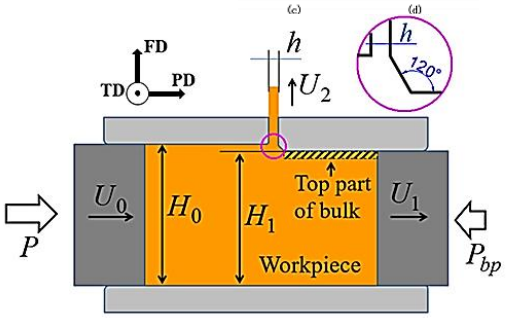
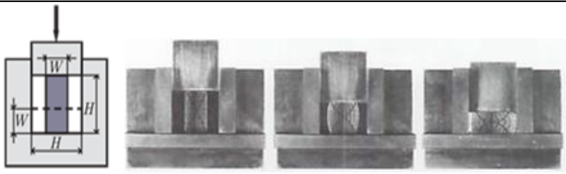
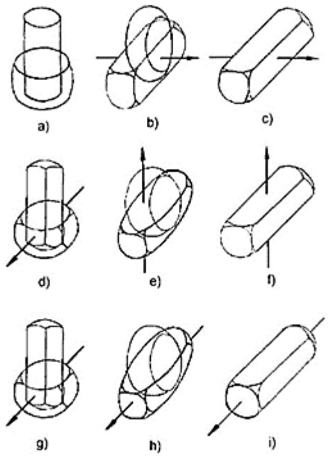
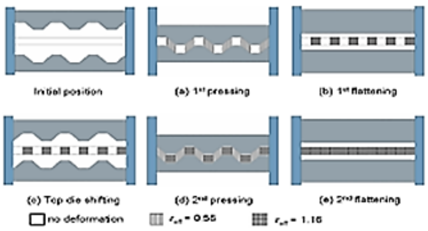
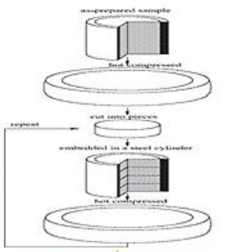
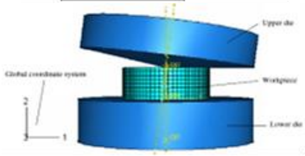
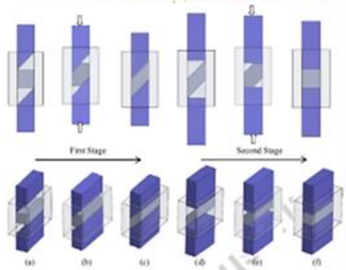
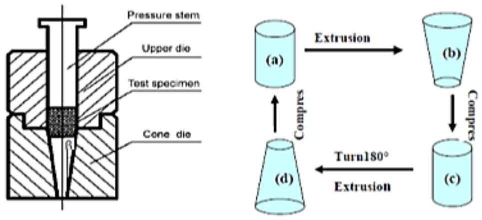
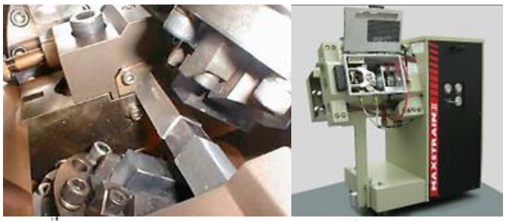
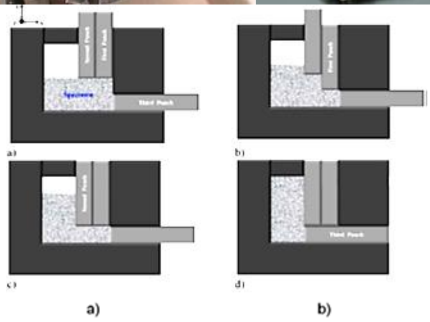
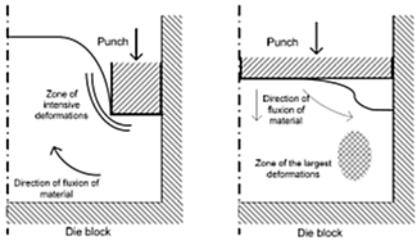
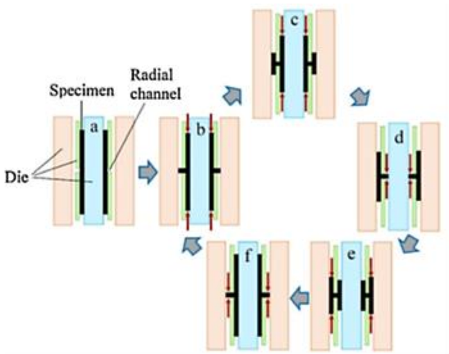
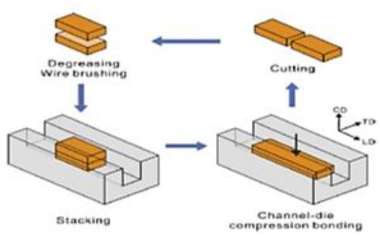
25	Compound extrusion		[195]
26	Alternate extrusion (AE)		[196]
27	Spin extrusion		[197]
28	Rotary extrusion (RT)		[198]
29	Plastic flow machining (PFM)	 	[199]

Table 5. Summary of different SPD techniques based on pressing/forging

	SPD technique	Illustration	[Ref.]
1	Multi axial forging/compression; Cyclic closed-die forging(CCDF)		[200-202]
2	Multi axial forging (open die)		[203-206]
3	Constrained groove pressing (CGP)		[207-209]
4	Cylinder covered compression (CCC)		[210]
5	Orbital rotary forging		[211,212]
6	Repetitive forging (RF)		[213]

7	Continuous variable cross-section Recycled extrusion (CVCE)		[214]
8	MAX strain (multi-axis deformation system)		[88,215]
9	Multi-axial incremental forging & shearing (MAIFS)		[216]
10	Alternate pressing & multiaxial compression		[217]
11	H-tube pressing (HTP)		[218]
12	Accumulative channel-die compression bonding (ACCB)		[219]

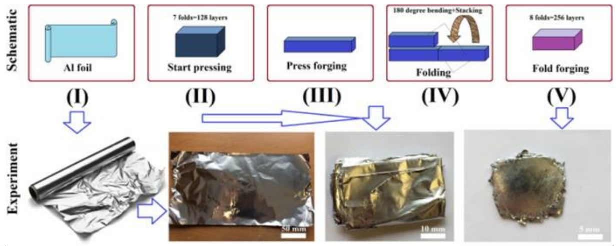
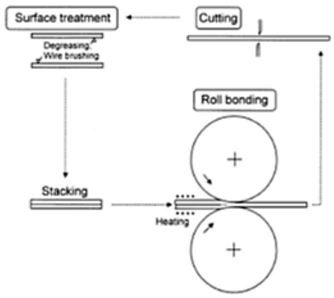
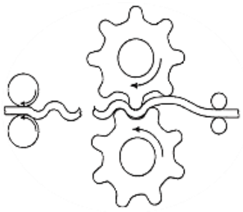
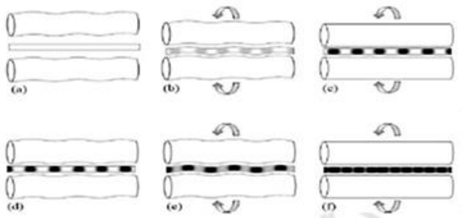
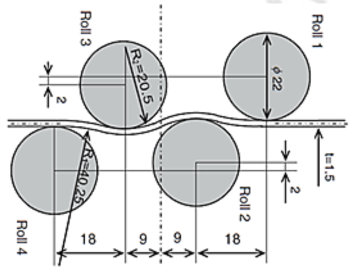
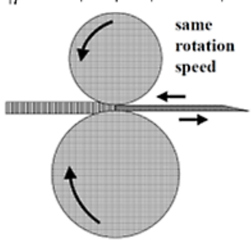
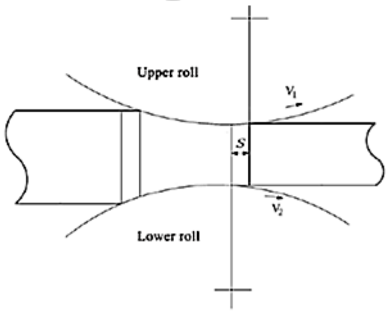
13	Accumulative fold-forging (AFF)		[220]

Table 6. Summary of different SPD techniques based on rolling

	SPD technique	Illustration	[Ref.]
1	Accumulative roll-bonding (ARB)		[14]
2	Repetitive corrugation & straightening (RCS)		[221]
3	Repetitive corrugation &straightening by rolling		[222]
4	Continuous cyclic bending (CCB)		[223]
5	Asymmetric rolling		[224,225]
6	New asymmetrical rolling		[226]

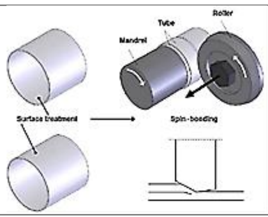
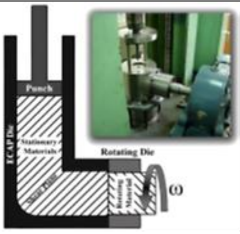
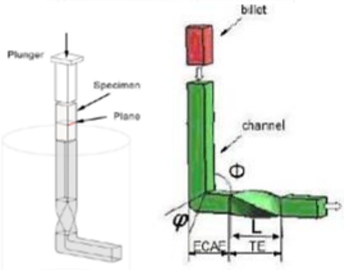
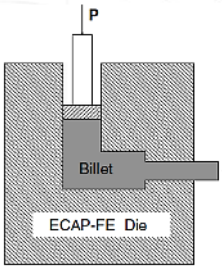
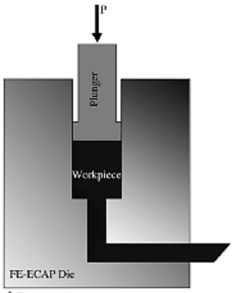
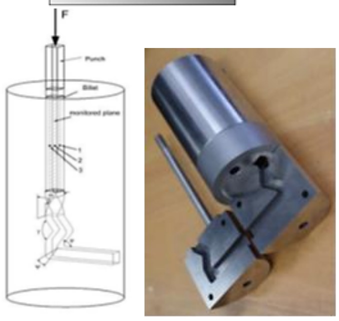
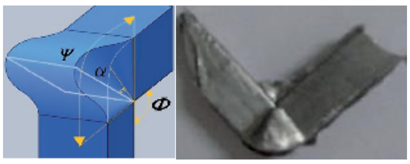
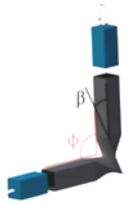
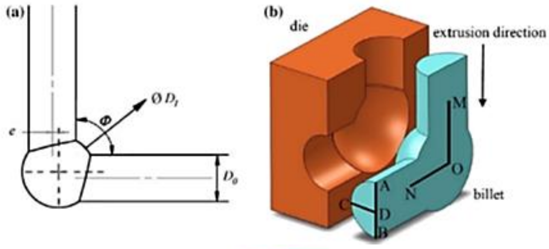
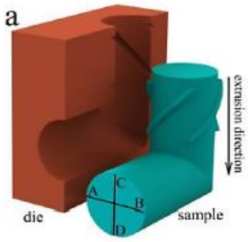
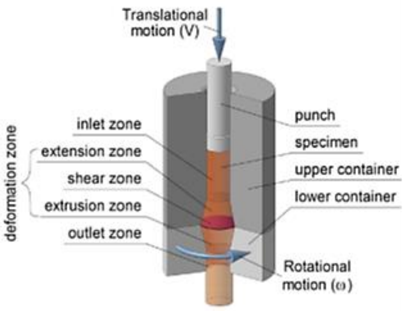
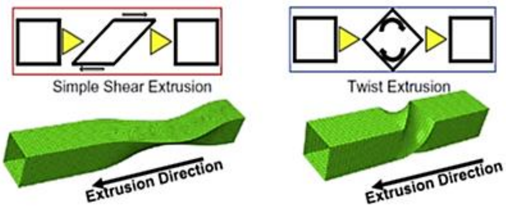
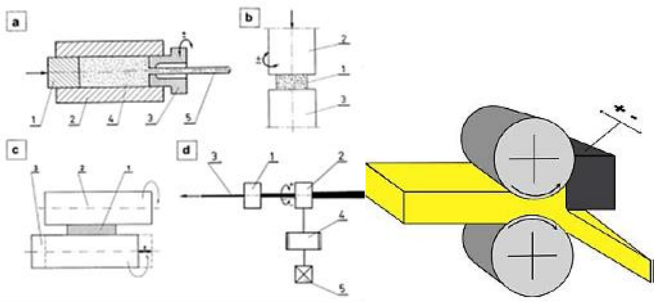
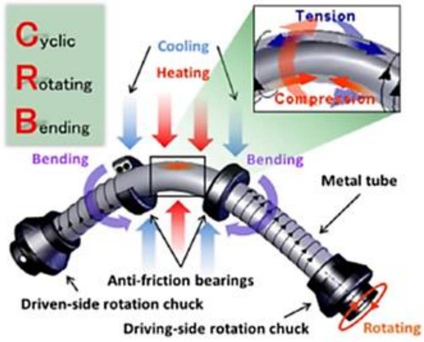
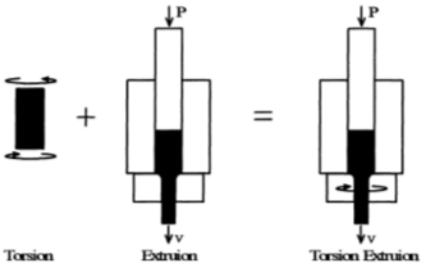
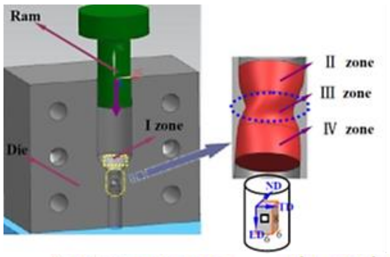
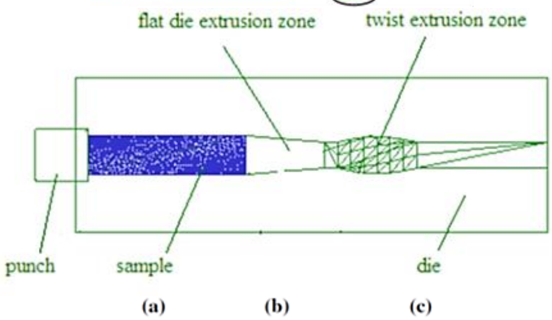
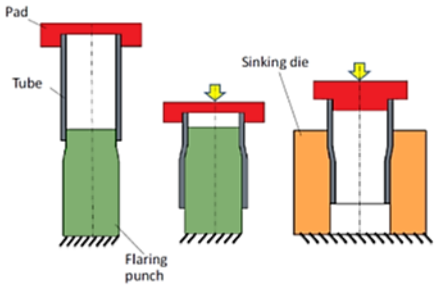
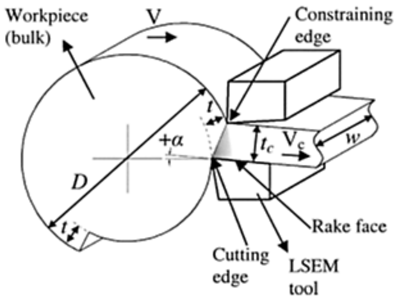
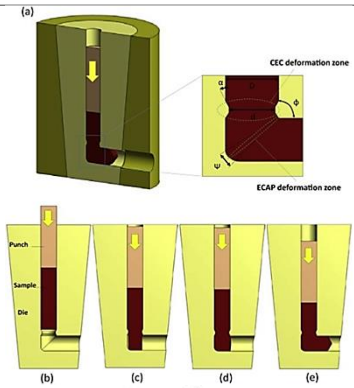
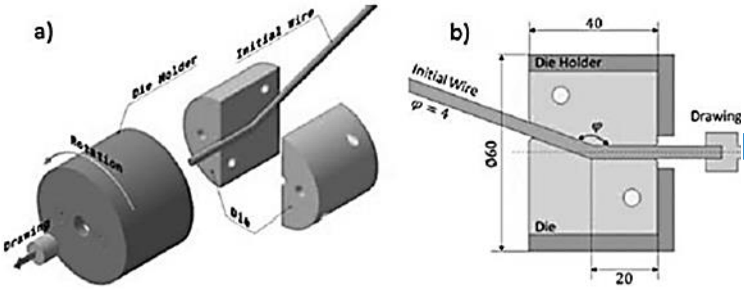
7	Accumulative spin bonding (ASB)		[227]

Table 7. Combined SPD techniques

	SPD technique	Illustration	[Ref.]
1	Torsional-equal channel angular pressing (T-ECAP) {ECAP+Torsion}		[228]
2	Twist channel angular pressing (TCAP) {ECAP+TE}		[229,230]
3	ECAP forward extrusion (ECAP-FE)		[231]
4	Forward extrusion ECAP (FE-ECAP)		[232]
5	Twist channel multi-angular pressing (TCMAP) {TE+MECAP}		[233]
6	Planar twist channel angular extrusion (PTCAE) {ECAP+SSE}		[234]

7	Symmetrical channels angular pressing (SCAP) {TE+ECAP+TE}		[235]
8	Expansion equal channel angular extrusion{ECAP+ CEE}		[236]
9	Spiral equal channel angular extrusion (Sp-ECAE)		[126]
10	High pressure torsion extrusion {CEE+HPT}		[237]
11	Tandem process of simple shear extrusion & twist extrusion (TST)		[157]
12	KOBO method		[238]

13	Cyclic rotating bending (CRB)		[239]
14	Torsion extrusion		[240,241]
15	Integrated forward extrusion & torsion deformation method		[242]
16	Compound twist extrusion/C-TE (TE+Ext.)		[243]
17	Cyclic flaring and sinking (CFS)		[244]
18	Large strain extrusion machining (LSEM)		[245]

19	Cyclic extrusion compression angular pressing (CECAP)		[246]
20	Equal channel angular torsion drawing (ECATD)		[247]