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A Review of Severe Plastic Deformation

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ABSTRACT: This article reviews about Ultrafine grained (UFG) materials processed by Severe Plastic Deformation. From the period of 1950's, the researchers made a fountain stone for this technique. Over the last decades, this SPD technique experienced an enormous growth among the research field. There was a development of different methods of SPD, production of various materials by SPD with improved and interesting results based on our requirement. Moreover, different post processing techniques will also help to enhance the property of the SPD processed material. This paper reviews the overall development of this technique, various methods of SPD, discussed about the enhancement of the properties and finally concluded with some specific challenges and issues faced by the modern researchers. It may be helpful to those who wants specialise in bulk nanomaterials produced by SPD.

***Keywords*: ** Severe plastic deformation; Ultrafine-grained materials; Nano-Structured Material; Properties.

I. INTRODUCTION

Grain size is a key factor which affecting nearly all aspects of the physical, mechanical and chemical behaviour of polycrystalline metals to the surroundingmedia. Hence, modification of grain size can able to design materials with desired properties. Physical, mechanical and chemical properties can benefit greatly from the reduction of grain size. One of the possible ways for the microstructural refinement of metals is Severe Plastic Deformation (SPD. Recent studies [1–4] toldaancient model for grain refinement which gives a path of modern era. The modern SPD technology begins from ancient work by P.W. Bridgman whodeveloped the techniques for materialsprocessing through a combination of high hydrostaticpressure and shear deformation [5,6]. In 1950s, Bridgman defined the process of SPD which evolved into new definition suitable for current scenarioas "any method of metal forming under an extensivehydrostatic pressure that may be used to impose a veryhigh strain on a bulk solid without the introduction of anysignificant change in the overall dimensions of the sampleand having the ability to produce exceptional grain refinement"[7]. Carreker and Hibbard [8]showed that the yield strength of high-purity copperbenefits greatly from grain. They also pointed outthat the effect of the initial grain size vanishes at strains largerthan 0.1 and for that reason the grain size has less influence on the strength under monotonic loading. Asimilar effect is also happen on fatigue property where the grain sizeof wavy-slip materials has no bearing on the fatigue limit.These observations can also be associated with dislocation substructure and size of thesubstructure.For the deformationand recrystallization behavior of metals and the effect ofevolving texture on the resultant properties,Gow and Cahn [9] explained thesignificance of crystallographic texture. Bell and Cahn[10] pointed out several features of mechanical twinning,which play a vital role in plastic deformation whenaccommodation by dislocation slip is hindered. Beck [11]emphasized the possibility of relieving theeffects of work-hardeningby post-processing recovery. Segalet al. [12]developed the method of equal-channel angularpressing (ECAP), which later evolved into SPD technique. As seen in thefollowing sections, these ideasunderlying the modern concepts of SPD.

Valiev et.al [13,14] begins the new possibilities for improvingthe properties of metallic materials given by SPD, which shows the relationship between theenhanced strength and the extreme grain refinementimparted by SPD processing to a range of metals andalloys. Over the last decade, the nano-SPD community which having animpressive group of researchers delivers a thousands of publicationson ultrafine-grained (UFG) and nanostructuredmaterials produced by SPD.Some more relevant articles on the subject can be found inthe proceedings of symposia on UFG materials [15,16] andconferences of nanoSPD [17,18]. Further useful sources arethe reviews [19,20], special issues of Advanced EngineeringMaterials [21], Materials Science and Engineering A [22]and Materials Transactions [23,24].

SPD processing techniques becomes so popular because of enhancing the strength characteristicsof conventional metallic materials in a peculiar way. It is up to the factor of eight for pure metalssuch as copper and 30–50% for alloys [7,25].In spite of impressive property improvement achievedfrom SPD techniques, its application by industries has beenrather inactive. But now-a-days, things are now starting tochange, and there is a common feeling in the nanoSPDcommunity that major breakthroughs in terms of industry scale applications of

SPD based technologies are about to applicable.In thisarticle we reviewed thatthe evolution of SPD process up to the current scenario and the possibilities to achieve future trends which are tobe expected from SPD processing technologies. Special importancehas been placed on the scientifically challenging aspects ofSPD rather on technological issues.

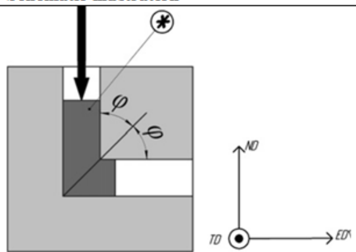
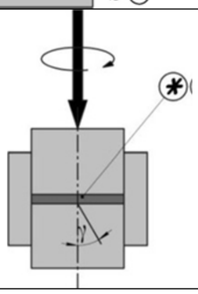
II. METHODS OF SPD

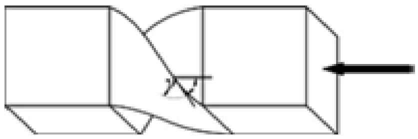
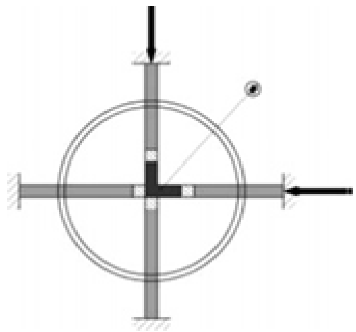
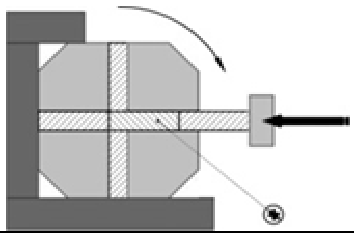
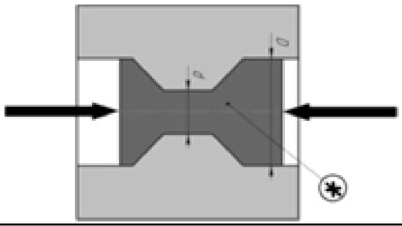
Among the methodsformulated for grain refinement,SPD techniques are more popular and are taken for thefocus of the present review. These techniques became greatpopularity because of their ability to produce considerablegrain refinement in fully dense, bulk scale work pieces,thus giving more promise for structural applications. Thegrain sizes achieved from SPD methods lie within the range ofsubmicrometer (100–1000 nm) and nanometer (<100 nm). Previously, SPD-processedmaterials with such grain sizes are generallyreferred to as nanoSPD materials [7].Now-a-days, it is named as nanostructured materialsaccording to the conventional definition. More comprehensivereviews have been focused on various nanostructured processingmaterials through SPD techniques [20,26–31]. We suggest the reader to theoriginal works for specific details and here only brief outlinefor SPD has been given.

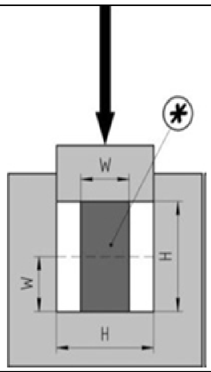
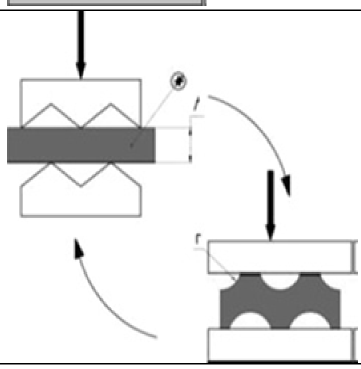
After the historic work by Bridgman mentioned above [6,33], Langford and Cohen [34] and Rack and Cohen [35] in 1960s revealed that the microstructure of Fe–0.003% C subjected to high strains by wire drawing wasrefined to sub grain sizes in the 200–500 nm range. Most of the sub-boundaries were low angle onthesemicrostructures, so it could not be regarded as proper UFG inthe sense of the commonly accepted definitions [7]. Indeed, it is the prevalence of high angle grain boundaries that is commonly considered a signature of UFG materials produced by SPD. This constitutes a clear boundary linebetween nanoSPD materials and nano-structured materials which is the conventional materials in modern days with subgrain structures produced by cold rolling. This difference make SPD process a step ahead from all other process for microstructurerefinement by deformation to gigantic strains.

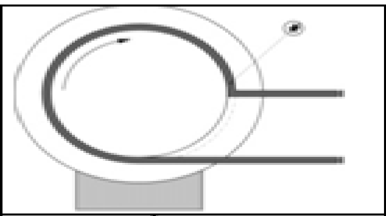
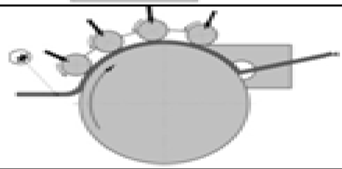
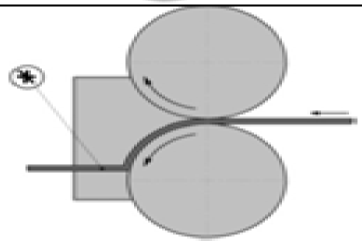
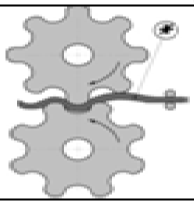
A large plastic strain imparted on a work-piece is a formidable and technically challenging task. It should requires a considerable importance on tool design, which on one hand during material forming, it should be durable enough to sustain repetitive high loads and on the

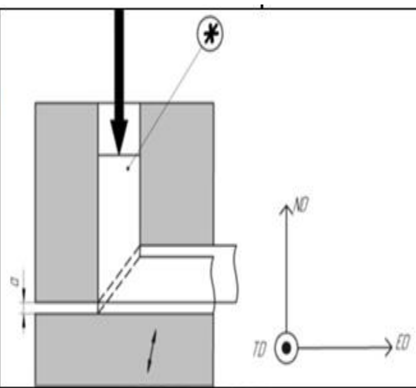
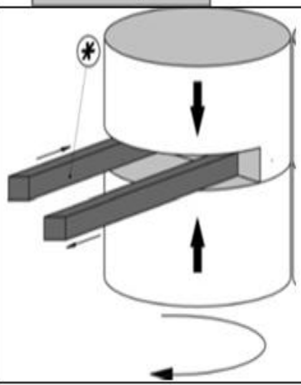
Table 1: Schematic illustrations of SPD techniques

Process	Schematic illustration	Equivalent strain	References
Basic processes a) Equal-channel angular pressing(ECAP)		$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\cot(\emptyset)$ N – Number of ECAP passes	[32]
b) High-pressure torsion (HPT)		$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\frac{\pi r}{l}$ r -distance from the axis t -thickness of the sample N - Number of revolutions	[34]

e) Twist extrusion (TE)		$\varepsilon_{eff}^{min} \approx 0.4 + 0.1\tan\gamma$; $\varepsilon_{eff}^{min} \approx N\frac{2}{\sqrt{3}}\tan\gamma$ Non-uniform Deformation γ–twist line slope N - Number of passes.	[61]
Derivative processes f) Repetitive side extrusion		Equivalent to ECAP	[65]
g) Rotary-die ECAP		Equivalent to ECAP	[66]
h) Cyclic extrusion compression (CEC)		$\varepsilon_{eff} = N\,4\ln\left(\frac{D}{d}\right)$ N -Number of cycles	[75]

i) Cyclic close-die forging (CCDF)		$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\ln\left(\frac{H}{W}\right)$ N - Number of cycles	[76]
j) Repetitive corrugation and straightening (RCS)		$\varepsilon_{eff} = N\frac{4}{\sqrt{3}}\ln\left(\frac{r+t}{r+0.5t}\right)$ N - Number of cycles	[72]

Continuous process n) ECAP-Conform			[37] [120]
o) Con-shearing			[121]
p) Continuous confined strip shearing (C2S2)			[122]
q) Continuous repetitive corrugating and straightening (RCS)			[73]

r) Incremental ECAP (I-ECAP)			[126]
s) Continuous high-pressure torsion			[127]

Other hand it should be suitable for materials processing without causing damage to the work piece. A peculiar feature of SPD processing is that the high strain is imposed on material without any significant change in the overall dimensions of the workpiece. This is attained due to special tool geometries which prevent free flow of the material and will able to produce a significant hydrostatic pressure. The presence of this hydrostatic pressure is a sign for attaining the high strains which is the requirement for achieving exceptional grain refinement. Many crystalline materials including brittle under ordinary conditions can ablebe deformed to large strains without failure. Nowadays many varieties of SPD techniques, which employ this generic feature of high hydrostatic pressure and are readily available for fabrication, gave a great variety of UFG materials.

2.1 Basic SPD processes

Equal-channel angular pressing (ECAP) is the most highlydeveloped SPD processing technique (Table 1a). When the billet passes throughthe area where the two channels meet,there is an introduction of a simple shear strain. The cross sectionaldimension of the billet remainsconstant. Therefore, the process permits repetitive pressing which leads to accumulation of verylarge strains. There are some different variants ofECAP processesbased on the rotations of the billet about thepressing axis between the passes are generallyleads to different results in terms of the microstructureand texture produced. The definitions of these different ECAProutes are referred below[13,14]. The key advantagesand fundamentals of ECAPwere first formulatedby V. Segal in older publications [12,38-42]. He defined ECAP as "a technique of deformation to bestow intensive, uniform and oriented simple shear formaterials processing". He also showed that ECAPis effective if (i) frictionis kept at minimum between the billet and the die walls; (ii) the angle between the channels isnearly to be 90º; and (iii) the sharp outer corner is fully filledwhich ensuring that the shear zone is as narrow as possible. The first requirement developed by implementing surface hardening ofthe channel walls, mobile walls [37,43], etc., and theintroduction of new effective lubricants [36,44]. The thirdrequirement is to understanding the significanceof back-pressure for processing of billets with uniformmicrostructure and improved mechanical properties[43,45,46]. By following Segal's philosophy, samples withuniform microstructure throughout the billet could be fabricated[47,48].

High pressure torsion (HPT) involves a combination of high pressure withtorsional straining (Table 1b). A main disadvantage of this method is thatonly small coin shaped samples can be processed, which is typically 10–15 mm indiameter and 1 mm in thickness[28]. The HPT process isprimarily used for research purposes due to size restriction.Another important issue on HPT is non-uniformity in deformation.In HPT process, theshear strain at the rotation axis should be zero and increasinglinearly in the radial direction if the geometry of the sampledoes not change. Thus, it shows that the material nearthe rotation axis of the work pieceisundeformed.Along with the other disadvantages, the compressive pressure andthe number of revolutions of the anvil are sufficiently large is also notableas showed in Fig. 1 [49–51]. Vorhauer and Pippan [52] emphasizedthis inability by the fact that it is virtually impossible tomake an ideal HPT deformation because of the misalignmentof the anvilsaxes. Alternatively, the development ofa uniform strain (Fig. 2) and homogeneousmicrostructure was decribed in terms of gradient plasticitytheory coupled with the microstructurallybased constitutive modelling [53, 54].

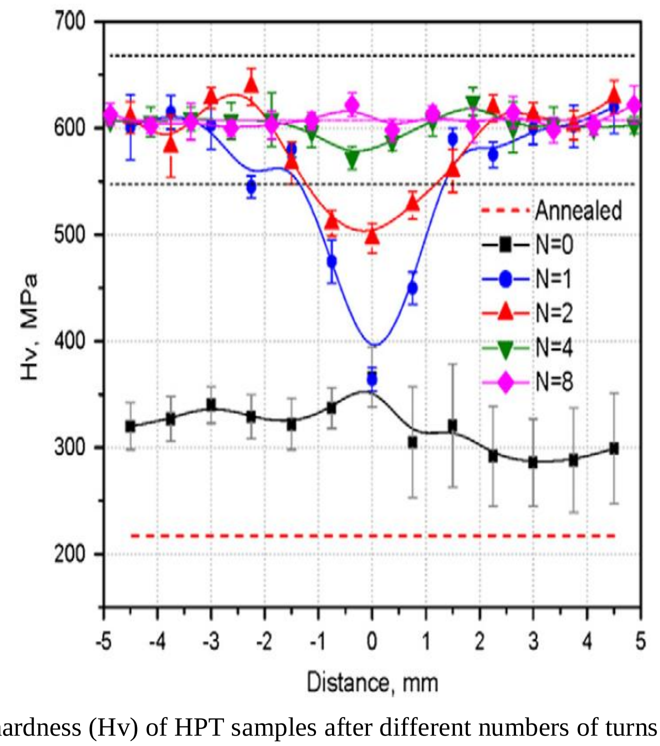


Fig. 1 Vickers microhardness (Hv) of HPT samples after different numbers of turns (N) as a function of the distance from the centre of the specimen [53].

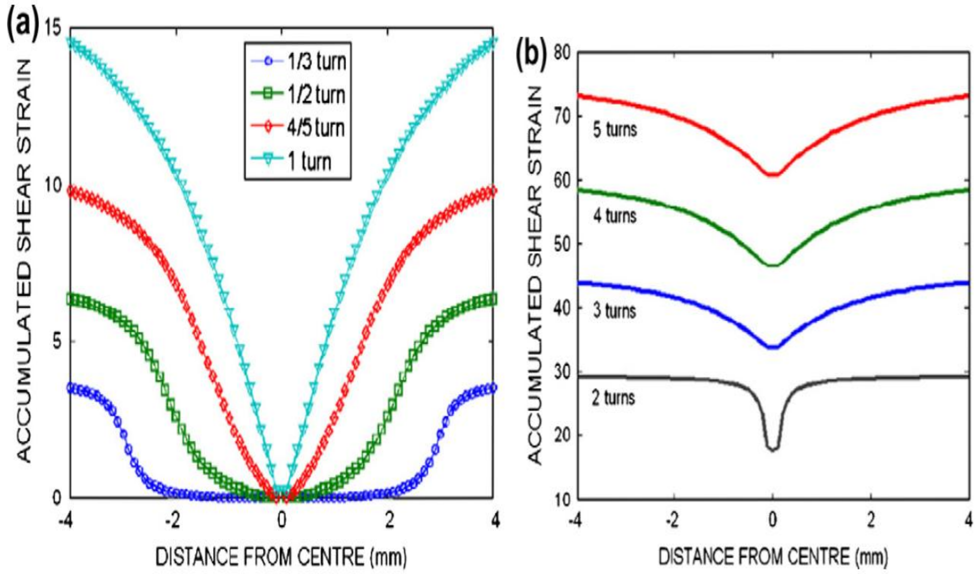


Fig. 2. Accumulated shear strain as a function of the distance from the torsion axis for the first-order gradient model [53].

Accumulative roll-bonding (ARB) was introduced by Saito et al. [55] in 1998 (Table 1c).This process overcomes major limitations likelow productivity,small work-piece size of the latter etc.., which are faced by ECAP and HPT. Saito et al. explains the process as a metal sheet is rolled to 50% thickness reduction. Then, the rolled sheet is cut in two halves and both halves are stacked together by preparing the contact surfaces with degreasing and wire brushing, thus restoring the original thickness of the sheet. The sequence of rolling, cutting, surface preparing and stacking operations are repeated continuously so that ultimately a large strain imparted on the material. ARB was successfully applied to commercial-purity (CP) Al, theAl–Mg alloy AA5083 and interstitial-free steel [56]. In addition, ARB can also be applied for the production of metal matrix composites by covering mixed powders and subjecting them to a process of rollbonding [57].

Multi-axial forging was introduced as a technique for grain refinement in 1990s [58–60] (Table 1d). It is also known as Multiple Direction Forging (MDF) which work under three orthogonal directions. Grain refinementduring MDF is usually associated with dynamic recrystallization due to the performance of the process under the temperature interval of 0.1–0.5T_m, whereT_m is the melting temperature.The method canbe used for grain refinement in brittle materialseven thoughin elevated temperatures. This method is also used for the manufacturing of large-sizebillets with microcrystalline (UFG) structures [61].

Twist extrusion (TE) is introduced byBeygelzimer et al. as a shear deformation process [62–64] (Table 1e). The process is simple where a billet is extruded through a twist die. The advantage of this process is its high upscalingcapacity. Non-uniform deformation is the main limitation for this process as like faced by HPTwhere the deformation nearer to the extrusion axis is smaller.Further,Orlovet al. [65] noted that this technique is not much efficientthan ECAP or HPT.

2.2. Derivative SPD processes

Although the above basic processes are successful, some exotic methods were developed for different shapes and sizes. These are named as derivative SPD processes. A list of these techniques is listed below:

- repetitive side extrusion [66];
- rotary die ECAP [67];
- parallel channel ECAP [68];
- hydrostatic extrusion [69–71]
- hydrostatic extrusioncombined with torsion [72];
- repetitive corrugating and straightening (RCS) [73–75];
- constrained groove pressing [76];
- cyclic extrusion–compression (CEC) [77];
- cyclic closed-die forging (CCDF) [78];
- cone–cone method (CCM) [79];
- cryogenic rolling [80,81];
- asymmetric rolling (ASR) [82];

- continuous frictional angular extrusion (CFAE) [83,84];
- friction stir processing (FSP) [85,86];
- super short interval multi-pass rolling (SSMR) [87,88];
- severe torsion straining (STS) [89,90];
- torsion extrusion [91];
- ECAP with rotation tooling in which the conventionalfixed die is replaced by rotating tools [92];
- reversed shear spinning [92];
- transverse rolling [92];
- non-equal channel angular pressing (NECAP) for plateshapedbillets [93];
- tube channel pressing [94];
- KOBO forming [95];
- high-pressure tube twisting (HPTT) for thin-walledtubes [96];
- cyclic expansion–extrusion CEE—a modified CEC process[97];
- simple shear extrusion [98,99];
- vortex extrusion [100];
- helical rolling [101];
- high-pressure sliding [102].

It is found that strength and ductility maygreatly increase,when ECAP process were combined with annealing / post ECAP processing like conventionalrolling, drawing or extrusion. The advantages of this technique to improve strength [103-105], modify texture [106] or ductility [107-109]. Finally, new integrated processing schemes have been recently developed and their derived properties are slightly improved when compared to the single process [110-112] (Table 2).

2.3. Continuous SPD techniques

There are large numbers of discrete steps in the above mentioned SPD methods and also not cost efficient. Moreover, basic SPD methods cannot able to deliver large work pieces and it is not applicable to industry level application.Thus, continuous SPD techniques have been introduced to overcome all the disadvantages. The varieties of continuous SPD techniques are explained below.

Continuous forming (CONFORM) is introducedby Etherington [120] with the aim of improving theefficiency of materials recycling (Table 1m). It was further developedby Segal et al. as continuous ECAP of bulkmaterials [37]. Raabet al. implemented these principleson Al and Ti rods [121]. In thisprocess, the work piece rod is placed in a groove within a rotatingshaft.By using frictional forces, the rotating shaft is driven forward and then it isextruded through an outlet cannel of the die. Saitoet al. modified this processfor processingof sheets or strips and named it as continuous shearing[122] (Table 1o).The modification of the CONFORM method for processing sheets or strips were proposed as Continuous confined strip shearing (C2S2) [123,124](Table 1p). Repetitive corrugating and straightening (RCS) is the one which can produce fine grainedstructures in metallic sheets or plates in bulk and as well it is a simple modification of rolling [74,75] (Table 1q). Incremental ECAP (I-ECAP) is introduced by Rosochowskiet al. which is the extension ofincremental metalforming operations, such as rolling or swaging and adapted it to ECAP by modifying it for processingof long billets [127] (Table 1r).

Table 2Mechanical properties of someSPDprocessed UFG metals and alloys

Material		Ref.	Processing	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	δ	σ_{fo} (MPa)
	AZ31	[114]	SC	50	170	10	40
			HR 370ºC	175	277	21	95
			HR + ECAP 4Bc 200ºC	115	251	27	95
		[115]	ST 420ºC 2 h + Q, ECAP4Bc 320-200ºC	180	286	9.4	40*
	ZK60	[110]	As cast	222	264	7.4	55
		[116]	IE 300ºC	310	351	17	150
	AA1050 (99.5%, CP Al)	[117]	O	28	70	40	28
			ECAP 8Bc	N/A	N/A	N/A	52
	1100	[118]	ARB 8	210	275		
Non agehardenable	AA5052 (Al 2.6Mg0.22Cr, 0.26Fe)	[119]	H38	255	290	7	
			ECAP 8, 150 ºC	394	421	9	

		[108]	ECAP + A 200 ºC, 6 h	350	370	10.5	
	AA 5056 Al–Mg		O	122	290	43	116
			H18	407	434	10	152
			ECAP 4C, 150 ºC	280	340	25	116
			ECAP 8Bc, 110 ºC	392	442	7	116
	AA5083 Al–Mg	[125]	O	145	290	22	
			H321	230	315	16	
			ST 350 ºC 1 h, ECAP 200 ºC, 8C	276	352	20	
Age-hardenable	AA6061 Al–Mg		O	150	270	48	40**
			T6	276	310	12	50**
		[128]	ST ECAP, 1, 125 ºC	310	375	20	80**
			ST ECAP, 4Bc, 125 ºC	380	425	20	<60**
	AA 2124		T851	455	492	7.2	125
		[130]	T851 + ECAE 8Bc, BP	330	602	7.2	290
	AA 7075		O	105	230	17	
			T6	503	525	9	
		[131]	ECAP 2Bc + NA 1 month	650	720	8.4	
	Al–4Mg–0.3Sc		HD	315	415	17	160
	Al–5.2Mg–0.32Mn–0.25Sc		HR	240	375	29	150
	Al–1.5Mg–0.2Sc–Zr	[132]	ST + ECAP, 8Bc, 150 ºC	340	360	13	135
	Al–3.0Mg–0.2Sc–Zr		ST + ECAP, 6Bc, 150 ºC	370	400	15	140
	Al–4.5Mg–0.2Sc–Zr		ST + ECAP, 6Bc, 160 ºC	230	410	29	150
	Al–6.0Mg–0.2Sc–Zr		ST460 ºC 24 h + ECAP, 4Bc, 320 ºC	240	260	8	100
	Al–5.7Mg–0.32Sc–0.4Mn	[133]	ST520 ºC 48 h + ECAP, 8C, 325 ºC	280	300	8	190
	AA6106 + 0.1Zr	[134]	ST, AG190 ºC 4 h	250	350	23	175
	AA6106d + 0.1Zr + 0.5Sc		ST + ECAP 4 + Ag190 ºC 4 h	570	590	9	225
			ST, AG190 ºC2 h	375	425	16	210
			ST + ECAP 4 + AG190 ºC2 h	625	650	8	275
Ti (grade 2)			CR	380	460	26	240
		[134]	ECAP 8Bc 400 ºC	640	810	15	380
		[135]	ECAP 8Bc 400 ºC, CR 87% ECAP	970	1050	8	420
		[136]	ECAP 6Bc 420 ºC	630	670	32	350
Ti (grade 4)		[137]	CR	530	700	25	350***
			ECAP 4Bc450–400 ºC, FD300 ºC	1150	1240	11	590***
			ECAP 4Bc450–400 ºC, F400–300 ºC, D, A350 ºC 6 h	1100	1250	13	610***
Cu (99.99%)		[138]	ECAP 8Bc	375	387		170
Cu–0.36Cr		[140]	ECAP 8CA, AG 500 ºC, 1 h	438	454	23	180
Fe (99.95%)		[139]	ECAP 4Bc	696	723	7	

$\sigma_{0.2}$ - conventional yield stress; σ_{UTS} - ultimate tensile strength; δ - elongation at break; σ_{fo} -endurance limit; O - as received condition; CR - cold rolling; HR - hot rolling; F - forging; D - drawing; MF - multistep forging; S - solution treatment; Q - quenching; A - annealing; AG - ageing; NA - natural ageing; BP - back pressure.
*R = 0.05
** R = 0
*** Rotation-bending test

Continuous high-pressure torsion was developed by Edalati and Horita [113]. It is known to be an advanced version of HPT techniquewhich can able to producesheets in a continuous fashion(Table 1s). Now, variety of SPD techniques is available. High hydrostatic pressure and the toolgeometry are their commonfeatures among them which permit multiple pass operation toachieve ultrahighstrains.Differences between the varieties of SPD methods are deformationmode, shape of work piece, the efficacy and the load involved.

III. PROPERTIES OF SPD PROCESSED MATERIAL

3.1 Strength and ductility

Strength and ductility are the most primary parameter of a material, which will assign all other mechanical characteristics. These properties are grain-size dependent because it is more affected by SPD process than any other mechanical properties.Moreover, many properties are directly governed by strength and ductility.Improving strength and ductility at the same time is considered as avery challenging task. For this, a strategy has been followed by Hall–Petch relationwhich relates yield stress σ_y and the grain size d:

$$\sigma_y = \sigma_0 + K_{HP} d^{-\frac{1}{2}}$$

Where σ_0 - friction stress

K_{HP}– constantfor a given material

As we seen earlier, there are number of various SPD processes are available (Table 1). In most of the cases, among them, the common trends seem to be clear that while enhancing the strength there will be a loss of ductility. It is illustrated in fig 5. where the variation of strength with number of ECAP passes. Combination of high flow stress and low strain-hardeningcapability is the main reason for loss of ductility. In some other cases, the tensile ductility of

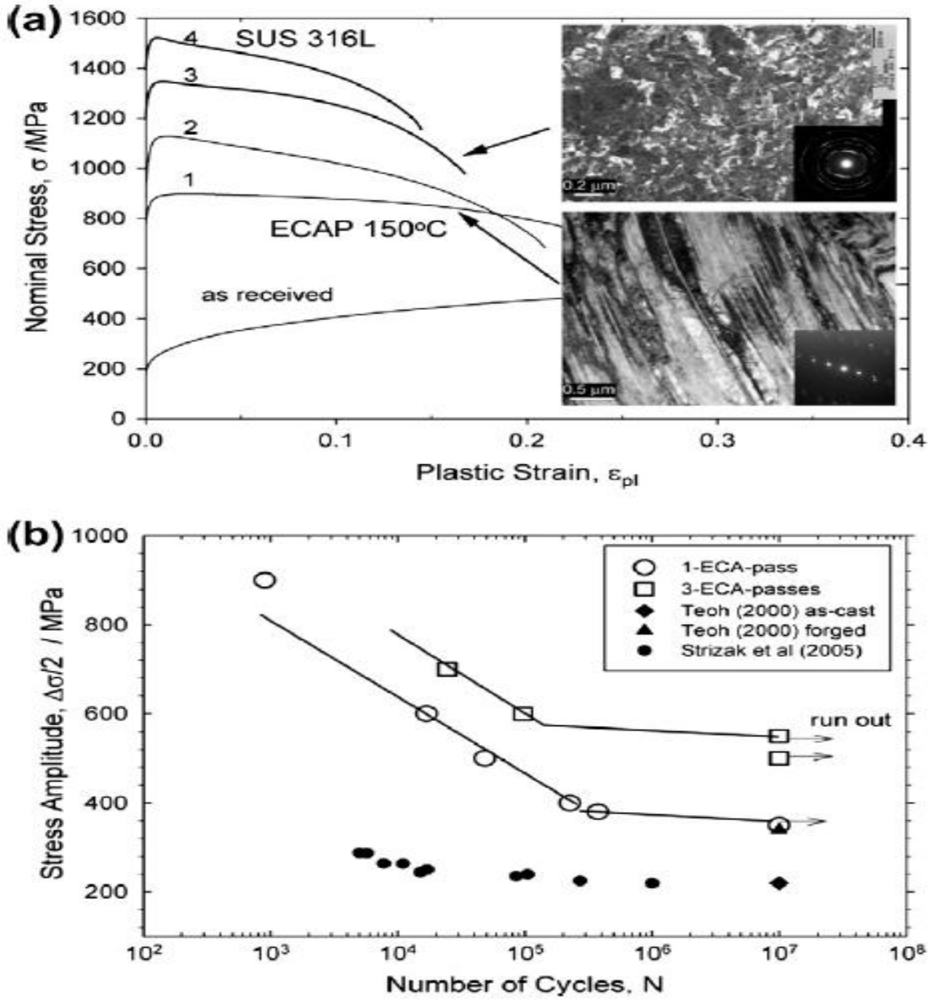


Fig 5. (a) Tensile stress–strain curves and (b) S–N fatigue plot for SUS 316L austenitic stainless steel after ECAP [147]

SPD processed materials is actually higher than that of the nanostructuredmaterials, for example, by cryomilling [141]. ECAP processed CP Al and ARB processed UFG Al and AA6016 are well revealed for enhancement of ductility [142,143]. However, Markushev and Vinogradov [132] pointed out that there is no improvement in ductility for non-age-hardenable Al–Mg alloys,such as AA5056. But, in age-hardenable Al alloys, it is found to be mostresponsive to SPD in terms of structure refinement,strength enhancement and ductility improvement [27,144–145].

As a result of SPD processing, uniform elongation does not commonlyimprove, but however, thematerial's resistance to localized plastic flow in the postneckingregime can increase remarkably.It was proved in Al alloy 6061[148], Ti [149] and Fe–36Ni Invar [150].The results for the enhancement of both strength and ductility showed on Ti [151], Cuand Cu–Al alloy [146,152,153], Cu–Zn [154], Al–Mg–Sc[155] and Al–Mg–Si [156]. Moreover,Zhao et al. [154] developed a multistepprocessing schedule which involves ECAP process followed bycryodrawing and cryorolling. They delivered a method for tremendousimprovement of strength and ductility.

Another strategy for the enhancement of strength coupled with improved ductility is named as delayed necking. It was achieved by mechanisms of deformation other than dislocation based ones, such as phase transformations or twinning. These mechanisms are widely used in steels, which are referred as transformation induced plasticity (TRIP) [157] and twinninginduced plasticity (TWIP) [158].Thetensileneck formation increases the stress triaxiality at the neck [159]. Because of this, the martensite nucleation increases in austenitic TRIP steels[140]. A local phase transformation with high stressconcentrations leads to local necking which enhances uniform elongation. Tao et al. [160] emphasized that the phase transformation provides a source of local strain hardeningwhenaustenite is replaced with martensite. Zhao et al. [161] demonstrated that Successful implementation ofthe twinning-based deformation strategy byusing the majoradvantages of TWIP alloys with low stacking fault energy(SFE). He found that UFG brassCu–10 wt.% Zn with a SFE of 35 mJ m^{-2}is much higher strength than UFG copper with aSFE of 78 mJ m^{-2}and the ductility of this material was also increased.It is illustrated in fig 5for a stable SUS 316L austeniticstainless steel. Because of its low SFE, the deformation twinning of this steel wasactivated during ECAP processing at 150 ºC. After three ECAP passes by routeBc, a nanoscale grain structure was formed.This nanostructuredsteel provides an excellent fatigue performance andimpressive thermal stability as well.

3.2 Fatigue and creep behavior

After the property of strength and ductility, fatigue and creep behavior is also an important property to analyze and a challenging task too. Mechanism to enhance strength strictly obeys Hall-Petch relation which is extended to sub-micron grain sizes and shows the dependency of grain sizes. But, however, based on the previous studies, our history shows thatfatigue behaviour does not exhibit strong grain-size dependence [162-165]. So far, when ECAP process is combined with other thermomechanicaltreatments, the fatigue of UFG metals were obtained.

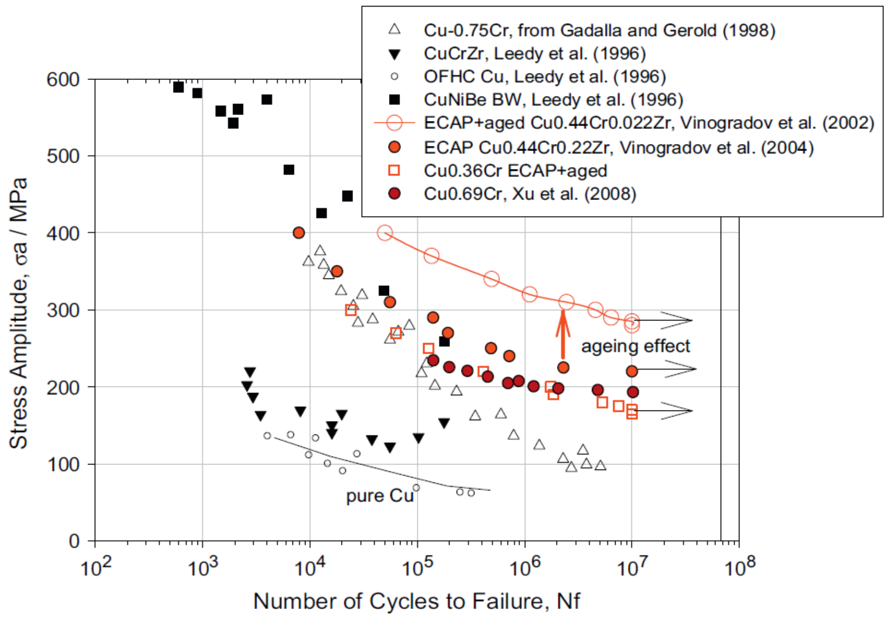


Fig. 6 The Wohler plot comparing fatigue lives and endurance limits for conventional and SPD-manufactured Cu-based alloys (Cu–Cr and Cu–Cr–Zr)

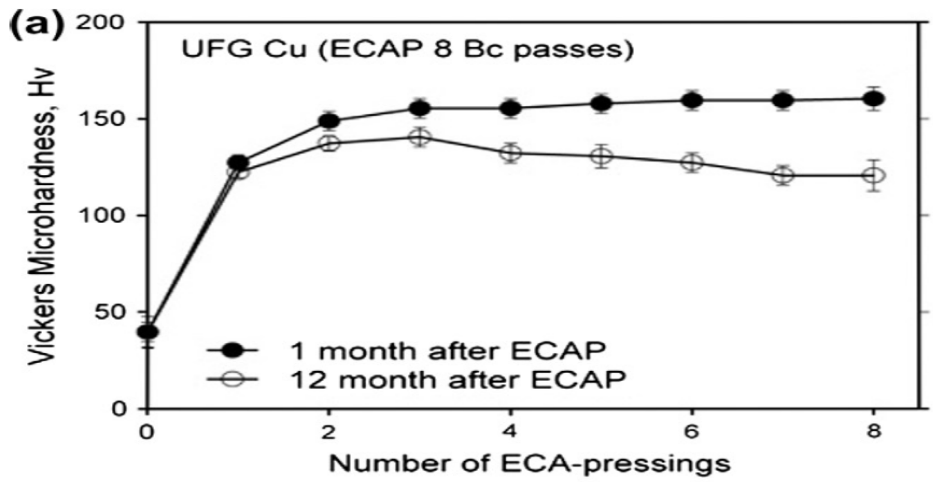
The research work on creep behaviour of UFG materials manufacturedby SPD is very little. Sklenicka et al.[166–168] emphasized the different factors which affectingthe creep performance of pure aluminium, pure copperand the binary Al–0.2 wt.%Sc alloy processed by ECAP. Thus it is noticed that the creep behavior strongly depends on number of passes, a decrease inthe creep resistance on every successivepass. It is due to the number of factors including microstructural changes, homogenization of themicrostructure and nanoporosityinduced by ECAP.

3.3 Thermal stability

Improving several properties of a material at the sametime is a very challenging task for materials science which provides multi functionality. Along with the strength and ductility, thermal stability, electrical conductivity and corrosive resistance are also most important in such cases that could not able to sacrificed. Depending on the material and their applications, a full list of properties according to their application needs to be obtained [169]. In most of the cases, thermal stability is avulnerable point of many SPD-treated materials. For example, SPD processed pure oxygen-freecopper provides poor thermal stability [170-172]. It has a tendency to recover during storage even at room temperature because during severe straining, annihilation of excess dislocations accumulated[173] (Fig. 11a). It is clearly shows thattherate of recoverydepends on the number of ECAP passes. For SPD-manufactured copper,there is no significant change in microstructureup to 120–150 ºC, but in the range of 150 to 250 ºC recovery followed by recrystallization andabnormal grain growth takes place (Fig. 11b). After annealing at 200 ºC for 10 min,there is a transformationof UFG structure into a bimodal one and at higher temperaturesit is evolved into fully recrystallized coarse-grained structure. It results in loss of stability depending on the purity of copper. Several processes have been used to overcome this type of limitations and to enhance multifunctional properties of SPD materials. Some of the processes includesgrain refinement, strain hardening, solidsolutionhardening and precipitation hardening.

When the above post processes are applied to UFG metals, the followingmeasures have beenfollowed.

(a) Post-process annealing carried under recrystallization temperaturerelieves internal stresses and increases work-hardening capacity. Thisimproves theoverall ductility of cold-worked materials[107,109,174].



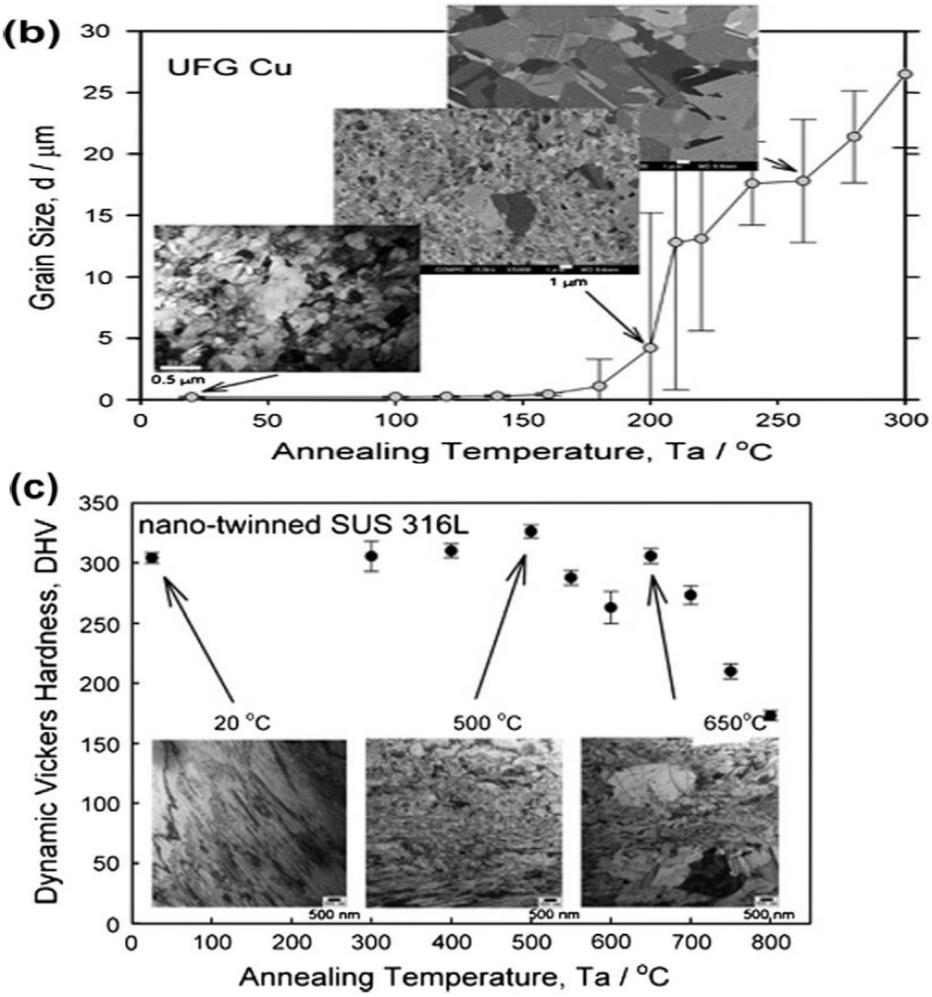


Fig. 11 (a)and (b) Thermal stability of ECAP processedcopper (99.96%), (c)SUS 316L stainless steel

(b) Titaniumwith hcp crystal lattice shows high thermal and microstructural stability under cyclic loading, retaining its UFG microstructure up to 450 ºC [175] and exhibitingno cyclic softening during Low Cycle Fatigue (LCF) [149,176] for ECAP processed iron.
(c) Stabilization by solutes which prevents grain coarsening by pinning of grain boundaries [47,179].
(d) Particle-induced stabilization [47,180,154].
(e) Grain boundary engineering was proposed byWatanabe [177,178] defines designing a high temperaturematerials exploits the idea of higher stabilityof special grain boundaries with low energy.

3.4 Corrosion resistance

For prospective engineeringapplications, corrosion resistance is an important property and improvement of this property is also a challenging task. Corrosion insingle-phase polycrystalline metals is mainly depending upon grain size and SPD processed strengthening mechanism should deteriorate the corrosion behavior. Corrosion could happen in three major aspects corrosion (chemical, electrochemical, pitting, etc.),stress corrosion cracking (SCC) and corrosion fatigue. Investigations carried out on only ECAP-processed copper based on these aspects [182-186]. In this investigation, SPD process as a better conclusion. While increasing the mechanical characteristics doesnot compromise the overall corrosion resistance andimproves the SCC and corrosion fatigue resistance also. This statement is confirmed by comparing ECAP processed copper with coarse-grained Cu polycrystals. There is a localized intergranular corrosion in coarse-grained Cu polycrystalswhere such a homogeneity of corrosion damage found in UFG Cu (Fig. 13a and b). These findings were followed by many researchers who found improved corrosion resistance of UFG Cu [187–188], Aland some Al-alloys [181,189–191], titanium [192],interstitial-free steel [193], austenitic stainless steels 316L[194] and 304 [195], FeCr [196], Mg [197] and Mg-basedalloy ZK60 [198].

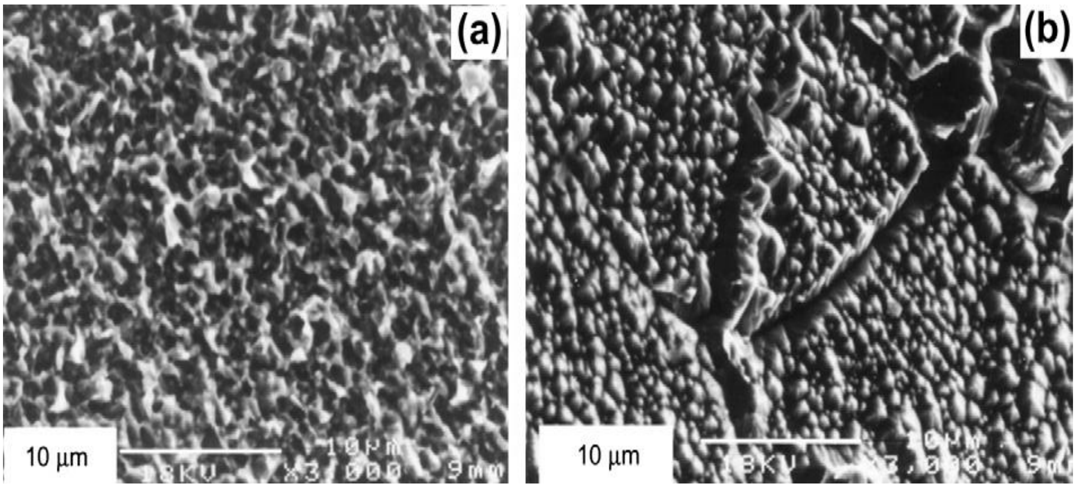


Fig. 13. SEM micrographs of ECAP copper (a) UFG stateafter ECAP and (b) a coarse-grained state after annealing at 823 K for 30 min [182].

IV. CONCLUSION

In these sections, we presented a brief history of SPD techniques, various SPD methods and the properties of SPD processed UFG materials. This review will serve as an introduction and reference for the readers those who are specializing in SPD process. This paper also gave fundamental problems of scientific challenges face by the industrial application and we highlighted those challenges throughout the manuscript.

However, there are large numbers of concepts which have establisheda thorough justification is missing in some concepts. Eventhough, the evidences for the responsibility ofbimodality of the grainstructure enhancing the good balance betweenstrength and ductility are delivered, there is some indications that the relationship between enhanced strength -ductility balance and the occurrence of a bimodalgrain structure are not proved. The enhancement of corrosion resistance and proliferation of the specimen results in some categorized where the surface phenomenon is affected by the link between surface and bulk properties. There is very limited research work has been carried out on this phenomenon.

SPD methods are basically extended from conventional metal working techniques and it is developed further for processing bulk materials. Now, this technique is extended further for some other purposessuch as efficient compaction of powders [199], particularlyfor producing alloys from blended elemental powders [200],and swarf [112,201]. Somehow, more new attractive applications were delivered [202]. Production ofarchitecturing and nanostructuring hybridmaterials usesadvanced SPD techniques. In particular,for producing a material in range of spiral architectures which is most beneficial for strength and ductility usestwist extrusion, HPT and some latest methods. This field willhave an outstanding future for the manufacturing ofinnovative materials and creative process design.

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