A Review on Accumulative Roll Bonding of Severe Plastic Deformation Process

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ABSTRACT

This article reviews about ultrafine grained (UFG) materials treated 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 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 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 want to specialize in bulk nanomaterials made by SPD.

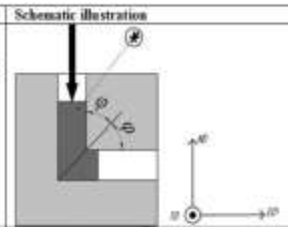
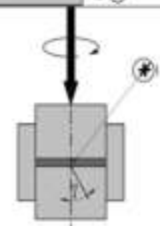
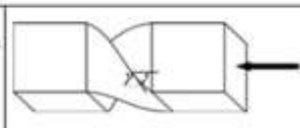
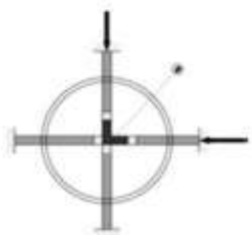
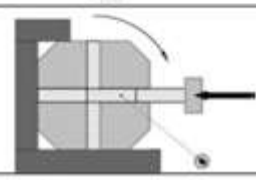
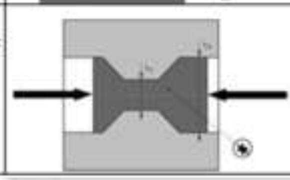
Keywords *Sever plastic deformation, Ultrafine grained materials, Nano materials properties*

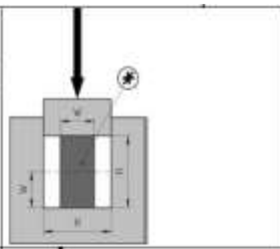
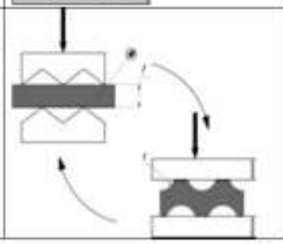
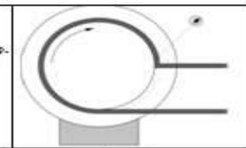
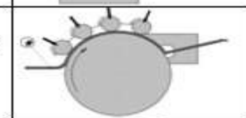
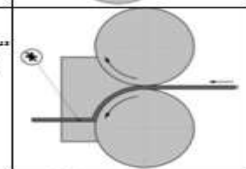
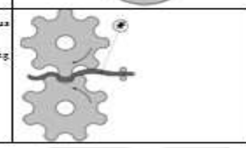
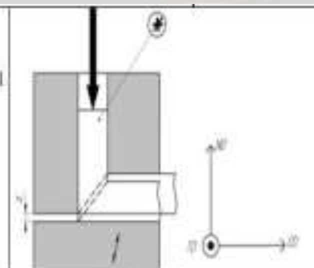
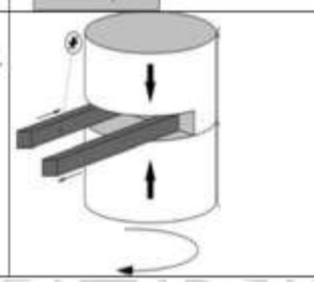
INTRODUCTION

Grain size is a main factor which affecting nearly all aspects of the physical, mechanical and chemical behavior of polycrystalline metals to the surrounding media. Hence, modification of grain size can able to design materials with preferred properties. Physical, mechanical and chemical properties can benefit greatly from the reduction of grain size. One of the possible ways for the microstructural modification of metals is Severe Plastic Deformation (SPD. Recent studies [1–4] told ancient model for grain refinement which gives a path of modern era. The modern SPD technology begins from ancient work by P. W. Bridgman who developed the techniques for materials processing through a combination of high hydrostatic pressure and shear deformation . In 1950s, Bridgman defined the process of SPD which evolved into new definition suitable for current scenarios any process of metal forming under an widespread hydrostatic pressure that may be used to execute a very high strain on a bulk solid without the overview of any important change in the overall dimensions of the sample and ensuring the capacity to produce unique grain refinement‖[7]. Carreker and Hibbard [8] showed that the yield strong point of high-purity copper benefits greatly from grain. They also pointed out that the outcome of the initial grain size vanishes at strains larger than 0.1 and for that reason the grain size has less impact on the strength under monotonic loading. A related effect is also happen on fatigue property where the grain size of wavy-slip materials has no bearing on the fatigue bound. These observations can also be related with dislocation substructure and size of the substructure. For the deformation and recrystallization behavior of metals and the effect of evolving texture on the resultant properties, Gow and Cahn [9] explained the significance of crystallographic texture. Bell and Cahn [10] pointed out several features of mechanical twinning, which play a vital role in plastic deformation when accommodation by dislocation slip is hindered. Beck [11] emphasized the possibility of relieving the effects of work-hardening by post-processing recovery. Segal et al [12]developed the method of equal-channel angular pressing (ECAP), which later evolved into SPD technique. As understood in the following segments, these idea sunder lying the modern concepts of SPD.Valiev et.al begins the new options for refining the properties of metallic materials given by SPD, which shows the relationship between the enhanced strength and the exciting grain improvement imparted by SPD processing to a range of metals and alloys. Over the last decade, the Nano-SPD community which having an impressive group of researchers brings a thousands of publications on ultrafine-grained (UFG) and nanostructured materials produced by SPD. Some more relevant articles on the theme can be found in the proceedings of symposia on UFG materials [15,16] and conferences of Nano SPD [17,18]. Further useful sources are the reviews [19,20], special issues of Advanced Engineering Materials [21], Materials Science and Engineering A [22]and Materials Transactions [23,24].SPD processing techniques becomes so popular because of improving the power features of conventional metallic materials in a peculiar method. It is up to the factor of eight for pure metals such as copper and 30–50% for alloys [7, 25].In spite of inspiring property improvement accomplished from SPD methods, its application by industries has been rather inactive. But now-a-days, things are now starting to change, and there is a common feeling in the Nano SPD community that major breakthroughs in terms of industry scale applications of SPD based technologies are about to applicable .In this article we reviewed that the evolution of SPD process up to the current scenario and the possibilities to achieve upcoming developments which are to be expected from SPD processing technologies. Special importance has been placed on the scientifically challenging facets of SPD rather on technological issues.

METHODS OF SPD

Among the methods formulated for grain improvement, SPD techniques are more popular and be situated taken for The effort of the present appraisal. These methods became great attractiveness because of their ability to produce significant grain improvement in completely compact, wholesale scale workpieces, therefore giving more ability for structural applications or uses. The grain sizes achieved from SPD methods lie within the range of sub micrometer (100–1100 nm) and nanometer (<100 nm). Previously, SPD-processed resources by such grain sizes are mostly raised to as Nano SPD materials [7]. Nowadays, it is according to conventional meaning. More all-inclusive reviews have materials through SPD techniques [20, 26–31]. We recommend the reader to the original mechanism for definite details and here only brief outline for SPD has been given. Afterward the historic work by Bridgman stated above [6,33], Langford and Cohen [34] and Rack and Cohen [35] in 1960s discovered that the microstructure of Fe–0.002% C subjected to high strains by wire drawing was refined to sub grain sizes in the 200–500 nm range. Most of sub-boundaries were low angle on the semi microstructures, so it could not regarded as suitable UFG in the logic of the usually accepted explanations [7]. Certainly, it is the prevalence of high angle grain boundaries that is generally considered a signature of UFG materials produced by SPD. This constitutes a clear boundary line among Nano SPD materials and nanostructured materials which is the conventional materials in modern days with sub grain structures produced by cold rolling. This difference make SPD process a step ahead from all other process for microstructure refinement 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 substantial importance on tool design, which on one hand during material forming, it should be durable enough to sustain repetitive high loads and on the Other hand it must be suitable for materials processing without causing damage to the workpiece. 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 able are 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. Table 1: Schematic illustrations of SPD technique

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)		$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\frac{\pi r}{t}$ r -distance from the axis t -thickness of the sample N - Number of revolutions	[34]
e) Twist extrusion (TE)		$\varepsilon_{eff}^{TE} \approx 0.4 + 0.1\tan\gamma$; $\varepsilon_{eff}^{TE} \approx N\frac{2}{\sqrt{3}}\tan\gamma$ 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 processes 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]

2.1. Basic SPD processes

Equal-channel angular pressing (ECAP) is the most highly developed SPD processing technique (Table1a). When the billet permits over the area where, two channels meet, here is an introduction of a simple shear strain. The cross-sectional measurement of the billet remains constant. Therefore, the procedure permits repetitive pressing which leads to buildup of precise huge strains. There are some different variants of ECAP processes based on the cycles of the billet about the pressing axis between the passes are usually leads to different results in terms of the microstructure and texture produced. The definitions of these dissimilar ECAP routes are referred below [13, 14]. The main benefits and basics of ECAP were first formulated by V. Segal in older publications [12, 38-42]. He defined ECAP as ―a method of deformation to give severe, uniform and concerned with simple shear for materials processing‖. He also defined that ECAP is effective if (i) friction is kept at minimum between billets and die walls; (ii) the angle between channels is nearly to be 90º; and (iii) the sharp outside corner is completely filled which confirming that the shear zone is as slim as conceivable. The first requirement developed by applying surface hardening of the channel walls, mobile walls [37, 43], etc., and the introduction of new effective lubricants [36, 44]. The third requirement is to understanding the implication of back-pressure for processing the billets with unchanging microstructure and developed mechanical properties[43,45,46]. By following Segal's philosophy, samples with uniform microstructure through the billet could be fabricated[47,48]. High pressure torsion (HPT) involves a combination of high pressure with torsional straining (Table1b). A main disadvantage of this technique is for only small coin shaped samples can be processed, which is normally 5–15 mm in diameter and 1to 2 mm in thickness[28]. The HPT process is mainly used for research purposes due to size limits. Another issue on HPT is non-uniformity in deformation. Micro hardness (Hv) of HPT samples after many numbers of turns (N) as a function of the space from the center of the sample [53] In HPT process, the shear strain at the rotation axis should be zero and increases linearly in the radial direction if the geometry of the sample does not change.Thus, it shows that the material near the rotation axis of the job or workpiece is unreformed. Along with the other difficulties, compressive pressure and the number of revolutions of the anvil are adequately large is also notable as presented in Fig.1 [49].Vorhauer and Pippin [52] emphasized this inability by the fact it is virtually difficult or impossible to make a perfect HPT deformation because of the misalignment of the axes. Alternatively, the growth of a uniform strain (Fig. 2) And similar microstructure was called in terms of gradient plasticity theory joined with the microstructurally based constitutive modeling.

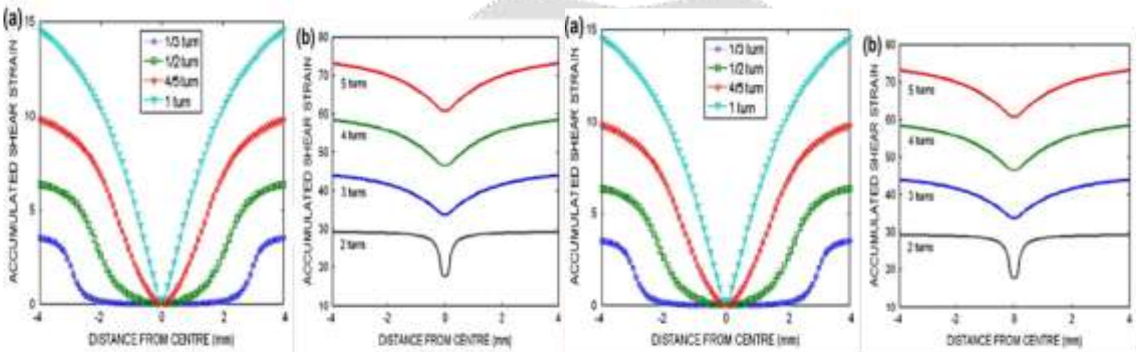
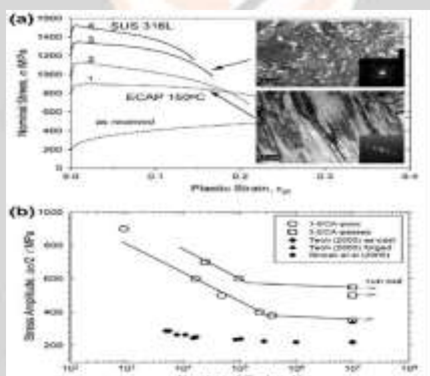


Fig 2. Accumulated shear strain as a function of distance from torsion axis for the first-order gradient model [53].Accumulative roll-bonding (ARB) was introduced by Saito et al. [55] in 1998 (Table 1c).This procedure overcomes key limitations similar to low productivity, small work-piece dimensions of the latter etc.., which are tackled by ECAP and HPT. Saito et al. describes the method as a metal sheet is rolled to 60% thickness decrease or reduction. Then, the rolled sheet is cut in two parts and both sheets are stacked together by making the contact surfaces with degreasing and wire brushing, so restoring the original thickness of the sheet. The order of rolling, cutting, surface area preparing and stacking jobs are repeated continuously again, so finally a large strain imparted on the material. ARB was successfully applied to commercial-purity (CP) Al, the Al-Mg alloy AA5083 and interstitial-free steel [56]. ARB can also be applied for the manufacture of metal matrix composites by covering mixed powders and exposing them to a process of roll bonding [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 modification during MDF is commonly related with dynamic recrystallization due to the performance of the process under the temperature interval of 0.1–0.5Tm, where Tm is the melting temperature. The method can be used for grain refinement in brittle material seven though in elevated temperatures. This method is also used for the manufacturing of large-dimensions billets with microcrystalline (UFG) assemblies [61].Twist extrusion (TE) is introduced byBeygelzimer et al. as a shear deformation process [62–64] (Table1e) The process is simple where a billet is extruded over a twist die. The benefit of this method is its high upscaling ability. Non-uniform deformation is the main limitation for this process as like faced by HPT where the deformation nearer to the extrusion axis is smaller. Further,Orlov et al. [65] noted that this technique is not much efficient than ECAP or HPT.2.2. Derived SPD processes.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]; Rotating die ECAP [67]; Parallel station ECAP [68]; Hydrostatic extrusion [69–71] Hydrostatic extrusion combined with torsion [72]; Repetitive corrugating and unbending (RCS) [73–75]; Constrained groove persistent [76]; Repeated extrusion–compression (CEC) [77]; Cyclic closed-die forging (CCDF) [78]; Cone–cone technique (CCM) [79]; Cryogenic rolling [80, 81]; Unequal rolling (ASR) [82]; Nonstop frictional angular extrusion (CFAE) [83, 84]; Friction stirring handling (FSP) [85, 86]; super short interval multi-pass rolling (SSMR) [87,88]; Severe torsion strain (STS) [89, 90]; Torsion extrusion [91]; ECAP in rotation tooling which the conventional stable die is exchanged by rotating tools [92]; Reversed shear rotating [92]; Transverse rolling [92]; Unequal channel angular persistent (NECAP) for plates happed billets [93]; Tube channel pressing [94]; KOBO creating [95];

High-pressure tube twisting (HPTT) for thin-walled tubes [96]; Cyclic increase–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 might be importantly increase , once ECAP method were combined with annealing / post ECAP processing like conservative rolling, drawing or extrusion. The benefits of this method to increase strength [103-105], adjust texture [106] , ductility [107-109]. In conclusion, fresh integrated processing schemes have been recently developed and their derived properties are somewhat raised when compared to the single process [110-112] III .PROPERTIES OF SPD PROCESSED MATERIAL

3.1 Strength and ductility

Strength and ductility are common 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 in same time is considered as a very interesting task. For this, a plan has been followed by Hall–Petch relation which relates yield stress σy and the grain size d:1$\sigma y = \sigma 0 + KHP\ d-$Where $\sigma 0$ - friction stressKHP– constant for a given materials 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 y. It is illustrated in fig 5.where the variation of strength with number of ECAP passes. Combination of high flow stress and low strain-hardening capability is the key reason for loss of ductility. In some other cases, the tensile ductility of contained plastic flow in the post necking regime 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], Cu and Cu–Al alloy [146,152,153], Cu–Zn [154], Al-Mg–Sc [155] and Al–Mg–Si [156]. Moreover,Zhao et al.



[154] developed Fig 5 (a)Tensile stress-strain curves (b) S–N fatigue plot for SUS 316L austenitic stainless steel after ECAP [147] SPD processed materials is in fact higher than that nanostructured materials, for example, by cry milling [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 progress in ductility for non-age-hard enable Al-Mg alloys, such as AA5056. But, in age-harden able Al alloys, it is found to be most receptive to SPD in terms of structure refinement, strength improvement and ductility perfection [27,144–145]. As a outcome of SPD processing, uniform elongation does not commonly improve, but however, the material's resistance to a multistep processing schedule which involves ECAP process followed by cry drawing and cry rolling. They delivered a method for tremendous improvement of strength and ductility. Another strategy for the enhancement of strength coupled with improved ductility is named as delayed Necking. It was accomplished by mechanisms of deformation other than displacement based ones, such as stage changes or twinning. These mechanisms are widely used in steels, which are referred as transformation induced plasticity (TRIP) [157] and twinning induced plasticity (TWIP) [158]. The tensile neck formation raises the stress trial finality at the neck [159]. Since this, the marten site nucleation increases in austenitic TRIP steels [140]. A local phase transformation with high stress absorptions leads to local necking which enhances uniform elongation. Tao et al. [160] highlighted that the phase conversion delivers a source of local strain hardening when austenite is replaced with marten site. Zhao et al. [161] verified that Successful implementation of the twinning-based deformation plan by

using the major leads of TWIP alloys with little stacking fault energy (SFE). He found that UFG brass–10 wt. % Zn with a SFE of 35 mJ m–2is much higher strength than UFG copper with a SFE of 78 mJ m–2 and the ductility of this material was also increased. It is exemplified in fig 5 for a stable SUS 316L austenitic stainless steel. Because oits low SFE, the deformation twinning of this steel was activated during ECAP processing at 150 ºC. After three ECAP passes by route, a nanoscale grain structure was made.

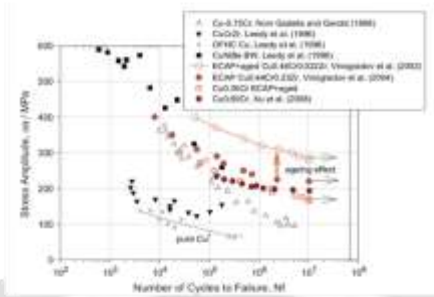


Fig. 6 The Wohler plot comparing fatigue lives and endurance parameters for conservative and SPD-manufactured Cu-based alloys (Cu–Cr and Cu–Cr–Zr)This nanostructured steel provides an outstanding fatigue performance and notable thermal stability as well.

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 towards sub-micron grain size and shows the need of grain sizes. But, however, based on the previous studies, our history shows that fatigue performance does not exhibit durable grain-size necessity [162-165]. So far, when ECAP process is combined with other thermomechanical treatments, the fatigue of UFG metals were gained. The research work on creep actions of UFG materials manufactured by Sever plastic deformation is very slight.Sklenicka et al.[166–168] emphasized the different factors which affecting the creep performance of pure Al, pure copper and the binary Al–0.2 wt. % Sc alloy processed by ECAP. Thus it is noticed that the creep behavior intensely depends on number of passes or cycles, a reduction in creep resistance on every successive pass. It is due to the number of factors including microstructural variations, homogenization of microstructure and Nano porosity induced by ECAP.

3.3 Thermal stability

Improving numerous properties in the same period is a very challenging task for materials science which provides multi-functionality. Along with the strength and ductility, thermal constancy, electrical conductivity and corrosive resistance are also most important in such cases that could not capable to sacrificed. Material and their application depends on, a list of properties according to their application needs to be obtained [169]. In most of the cases, thermal stability is vulnerable point of various SPD-treated materials. For example, SPD handled pure oxygen-free copper provides unfortunate thermal stability [170-172]. It has propensity to recuperate during storage even at room temperature because during severe straining, annihilation of excess dislocations accumulated [173] (Fig. 11a). It is clearly shows that ,rate of recovery depends on the number of ECAP passes. For SPD-manufactured copper, there is no significant change in microstructure up to115–150 ºC, but in the range of 150 to 250 ºC recovery followed by recrystallization and abnormal grain growth takes place (Fig. 11b). After hardening at 200 ºC for 10 min, there is a transformation of UFG structure into a bimodal one and at higher temperatures it 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 include grain refinement, strain hardening, solid solution hardening and precipitation hardening. When the above post processes are applied to UFG metals, the following measures have been followed. (a) Post-process annealing carried under recrystallization temperature relieves internal stresses and increases work-hardening capacity. This develops the whole ductility of cold-worked materials

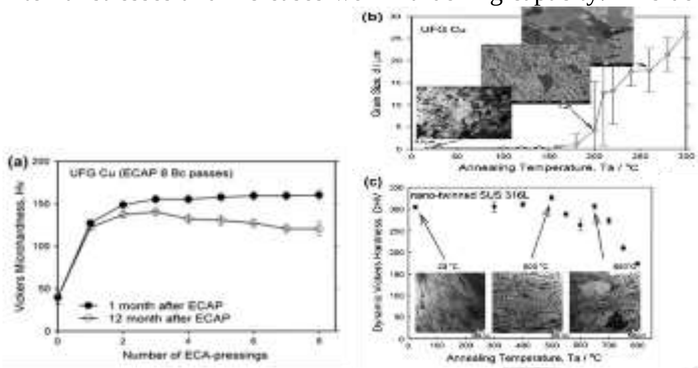
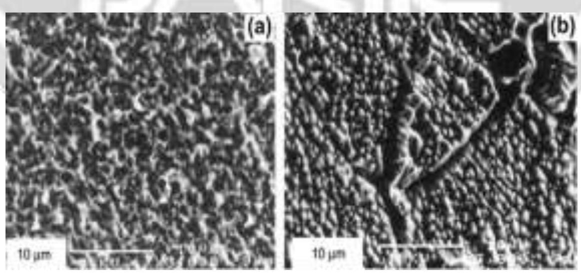


Fig. 11 (a)and (b) Thermal stability of ECAP processed copper (99.96%), (c)SUS 316L stainless steel(b) Titanium with hcp crystal lattice indicates high thermal and microstructural stability in cyclic loading, recollecting its UFG microstructure up to 450 ºC [175] and exhibiting no cyclic softening during Low Cycle Fatigue (LCF) [149,176] for ECAP treated 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 advised by Watanabe [177,178] defines designing a high-temperature materials adventures the clue of advanced stability of special grain boundaries with low energy.

3.4 Corrosion resistance

Prospective engineering applications, corrosion resistance are an important property and Improvement of this property is also a challenging task. Corrosion in single-phase polycrystalline metals is mainly depending upon grain size and SPD processed strengthening mechanism should deteriorate the corrosion behavior. Corrosion could happen in three main features (chemical, electrochemical pitting), 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 does not compromise the overall corrosion resistance and improves the SCC and corrosion fatigue resistance also. This statement is confirmed by comparing ECAP processed copper with coarse-grained Cu poly-crystals there is a localized intergranular corrosion in coarse-grained Cu polycrystals where such homogeneity of corrosion damage found in UFG Copper (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], Iron ,Cr [196], Mg [197] and Magnesium -based all



SEM micrographs of ECAP copper (a) UFG state after ECAP and (b) coarse-grained state after annealing at 820K for 25min.

4. CONCLUSION

In these sections, we presented a brief past of SPD techniques, many SPD approaches and the properties of SPD processed UFG materials. This review will help as an introduction and 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 established thorough explanation is mislaid in some ideas. Even though the evidence for the responsibility of bimodality of the grain structure enhancing the respectable balance between strength and ductility are delivered, there are some suggestions that the connection between enhanced strength-ductility equilibrium and the occurrence of a bimodal grain construction are not verified. The improvement of corrosion resistance and propagation of the sample outcomes in some categorized where the surface phenomenon is affected by link between surface and substance 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 drives such as efficient compaction of powders, principally for creating alloys from combined elemental powders [200],and swarf . Somehow, more new attractive applications were delivered . Production of architect ring and Nano structuring hybrid materials uses advanced SPD techniques. In particular, for producing a material in range of spiral architectures which is most helpful for strength and ductility uses twist extrusion HPT and some latest methods. This field will have an outstanding future for the manufacturing of innovative materials and creative process design.

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