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A Critical Review on Severe Plastic Deformation

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ABSTRACT

Severe Plastic Deformation (SPD) is defined as metal forming process in which a very large plastic strain is imposed on a bulk process in order to make an ultra-fine grained metal. The objective of the SPD process is to produce light weight parts by using high strength metal for the safety and reliability of micro parts and for environmental harmony. In the current work, SPD techniques like Equal Channel Angular Pressing (ECAP), Accumulating Roll Bonding (ARB), Repetitive Corrugation and Straightening (RCS), High Pressure Torsion (HPT), Reciprocating Extrusion Compression (REC), Severe Torsion Straining (STS), Cyclic Closed Die Forging (CCDF), Super Short Multi-pass Rolling (SSMR), Cyclic Channel Die Compression (CCDC), Mechanical Alloying, Asymmetric Rolling etc., are reviewed.

Keywords: Ultrafine grain materials, severe plastic deformation, Forming, Strain, Metal.

I. INTRODUCTION

The Severe Plastic Deformation(SPD) is generic describing group of **Metalworking** techniques involving very large strains, typically involving a complex stress state or high shear, resulting in a high **Defect density** and **equiaxed** "**ULTRAFINE GRAIN" (UFG)** size (d<500nm) or **Nano Crystalline(NC)** structure(d<100nm).

Process with Severe Plastic Deformation (SPD) may be defined as metal forming process in which an ultra-large plastic strain is introduced into a bulk metal in order to create ultra-fine grained metals [1-7]. The main objective of a SPD process is to produce high strength and light weight parts with environmental harmony.

In the conventional metal forming process such as rolling, forging and extrusion the imposed plastic strain is generally less than about 2.0. When multi-pass rolling, drawing and extrusion are carried up to a plastic strain of greater than 2.0, the thickness and diameter become very thin and are not suitable to be used for structural parts. In order to impose an extremely large strain on the bulk metal without changing the shape, many SPD have been developed.

Various SPD process such as Equal Angular Pressing(ECAP), Accumulative Roll Bonding(ARB), High Pressure Torsion(HPT), Repetitive Corrugation and Straightening(RCS), Cyclic Extrusion Compression(CEC), Severe Torsion Straining(STS), Cyclic Closed-Die Forging(CCDF), Super Short Multi-pass Rolling(SSMR), Cyclic Channel Die Compression(CCDC), Mechanical Alloying, Asymmetric Rolling, Surface Treatments, Mechanical Milling have been developed.

ECAP, ARB and HPT process are well-investigated for producing ultra-fine grained metals. It is known that the metals produced by these processes have very small average grain sizes of less than 1micro meter with grain boundaries of mostly high angle disorientation.

The structural changes caused by SPD are reflected in improved mechanical properties of metals. The reported effects include increased hardness and yield stress, both featuring tendency to saturation. The drawback of ultrafine grained structure materials is their limited ductility [8-9].Some other research revealed increased ductility and toughness as well as improves dumping and physical properties. The fine grained structure of UFG materials obtained by SPD leads to super plastic behaviour of these materials at lower temperature and yet with higher deformation rates. Various aspects of structural changes caused by SPD have been the research goals in laboratories worldwide. Hundreds of papers are published each year in distinguished journals and conferences proceeding (see proceeding of two TMS conference on UFG structure and development and properties evaluation [10-11]). Today most effort is paid to the study of the mechanism of material flow and grain subdivision when low strains and high strains are considered at the SPD. Usually, in dependence of the applied deformation methods (processing conditions) when different strain (von mises) at the deformation is developed, the various structures can be found in deformed materials. At low strain the orientation splitting and micro shear banding are mechanisms, which contributes to grain subdivision and cell bands structure dominates within deformed bands. When medium and higher strains are effective the lamellar HAGB structure, ribbon grains and formation of submicron grains structure dominates in deformed materials. The repetition of the straining process is required to obtain a large strain and desired structural changes.

When studying micro structure in SPD materials the evolution and the character of the new interfaces appears as a very important property with respect to evolution their influence on the mechanical properties.
Considering the deformation processing condition the heterogeneity in microstructure formation was often observed across the bulk specimen in dependence of the strain introduced [12]. Anticipating commercialization attempts, this work address the processing issues; a choice of major SPD process will be presented.

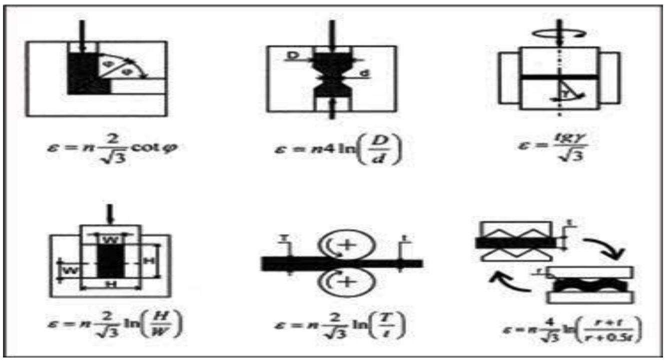

Figure 1. Schematic Representation of Severe Plastic Deformation of Metals.

II. SPD EXPERIMENTAL PROCESS

Obtaining large plastic deformation is a difficult task since in most metal forming process it is limited by either material or tool failure. Few processes such as accumulative rolling and multi-pass drawing enable large plastic deformation to achieve; however, metal foils or micro wires produced by these processes are not necessary the billet forms required. Therefore, special metal forming processes, capable for producing SPD without a major change in the billet should follow:
a)simple concept; b) how do you do it; c) does it really work it; e) is it any use. Among these can be included the following major SPD processes:

- Equal channel angular pressing(ECAP, segal,1977);
- High pressure torsion (HPT, valiev at al,, 1989);
- Accumulative roll bonding (ARB, saito , tsuji, utsunomiya, sakai, 1998);
- Reciprocating extrusion-compression (REC,J .and M.Richert, Zasadzinski, Korbel, 1979);
- Cyclic close die forging (CCDF,Gosh, 1988);
- Repetitive corrugation and straightening (RCS, Zhu, lowe, Jiang, Huang, 2001);
- Sever torsion straining(STS)
- Super short multi-pass rolling(SSMR)
- Cyclic channel die compression(CCDC)
- Mechanical alloying
- Asymmetric rolling
- Surface treatments

A. EQUAL CHANNEL ANGULAR PRESSING:

Equal channel angular pressing (ECAP, sometimes called as equal channel angular extrusion) was developed in the 1977. In this process, a metal billet is pressed through an angled (typically 90 degrees) channel. To achieve optimal results, the process may be repeated several times, changing the orientation of the billet with each pass. This produces a uniform shear throughout the bulk of the material [13].

ECAP is unique because significant cold work can be accomplished without reduction in the cross sectional area of the deformed workpiece. In conventional deformation processes like Rolling, Forging, Extrusion, and drawing, strain is introduced by reduction in the cross sectional area. ECAP produces significant deformation strain without reducing the cross sectional area. This is accomplished by extruding the work piece around a corner. For example, a square cross section bar of metals is forced.

Though a channel with a 90 degree angle. The cross section of the channel is equal on the entry and exit. The complex deformation of the metal as flows around the corner produces very high strain because the cross section remains the same, a work piece can be extruded multiple times with each pass introducing additional strain.

The Hall- petch relationship between the grain size and the level of yield strength. This relationship can be used in extensive interval of grain sizes, up to several dozens of manometers [14].

$\sigma_y = \sigma_0 + Kd^{-1/2}$ Eq [1]

Where [σ_y] is flow stress, [σ_0] and [K] are constants, [d] is grain size

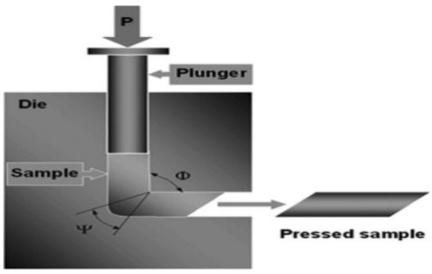

Figure 2. Schematic Representation of ECAP Process

B.HIGH PRESSURE TORSION:

High pressure torsion (HPT) can be traced back to the experiments that won **Percy Bridgman** the1946 **Nobel Prize in physics** though its use in metal processing is considerably more recent. In this method, a disk of the material to be strained is placed between 2 Anvils. A large compressive stress (typically several **gig pascals**) is applied. While one anvils rotated to create a **torsion** force. HPT can be performed un constrained, in which the materials is free to flow outward, fully constrained , or to some degree between in which outward flow is allowed, but limited [15]. During the constrained HPT process, the material experiences shear deformation between a fixed and rotating anvil, without losing its original dimensions.

HPT is generally conducted using a thin disk which is placed between anvils, subjected to a high applied pressure, and then processed by tensional straining through rotation of one of the anvils. The strain imposed in HPT may be estimated using the schematic illustration in fig[3].

For a small rotation, dө,, corresponding to a displacement dl, it follows that dl = rdө so that the shear strain, dɤ, is given by rdө/h where r and h are the radius and thickness of the disc, respectively. putting Ө= 2лN, it follows that the equivalent von- misses strain, $\mathcal{E}_{eq,}$ is given by an expression;

$\mathcal{E}_{eq,=}$ 2лNr/ h $(3)^{1/2}$.......Eq[2]

where N is the number of turns of the anvil. Inspection of eq[2] shows that the strain imposed in HPT varies the position on the disk. Specifically, it reaches maximum at the edge of the disc whereas the strain is reduced to zero at the centre where r=0. This suggests that the microstructures introduced in HPT processing extremely in homogeneous and they will vary as functions of the radial position within each disk. [16].

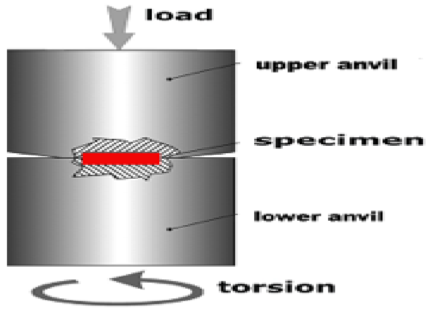

Figure 3. Schematic representation of hpt process.

C. ACCUMULATIVE ROLL BONDING:

In accumulative roll bonding (ARB), two sheets of the same material are stacked, heated (to below the **recrystallization** temperature). and **rolled,** bonding the 2 sheets together. This sheet is cut in half, the 2 halves are stacked, and the process is repeated several times. Compared to other SPD process. ARB has the benefit that it does not require specialized equipment or tooling, only a conventional rolling mill. [17].

However, the surfaces to be joined must be well-cleaned before rolling to ensure good bonding. Suppose the strip with initial thickness t_o rolled with 50% reduction in each cycle the thickness t_n of individual layer after n cycles can be calculated according to formula.

t_n $= t_o / 2^{л}$ eq[3]

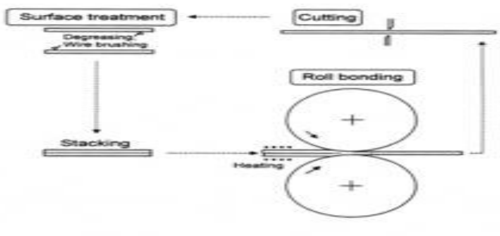

Figure 4. schematic of accumulative roll bonding

D. RECIPROCATING EXTRUSION COMPRESSION:

J.Richert et al. Came with the idea of cyclic reciprocating extrusion compression (RE) [18-19].REC involves the cyclic flow of metal between the alternating extrusion and compression chambers, the deformation effect could obviously be achieved with the frame/die fixed and the movable punches or vice versa. While the micro-structural results of the REC have been published widely, the mechanics of the process received less attention. Some results for REC of cylindrical billets are available, where a simplified stress analysis as well as closer to real condition Finite Elements Method (FEM) simulation shed some light on the deformation process. Results obtained from these analyses revealed that some sections with a hydrostatic stress state and other sections where the yield condition is met. This means that there is an elastic unloading in the transition zone between the two chambers of the die.

In the stress area, the stress path comprise primary yielding of the material due to extrusion, unloading into the elastic domain and secondary yielding by compression on the opposite side of the yield surface.

The forming force as well as tool pressure depends very much on friction. The active force and die pressure for low carbon steel obtained at simulation with friction and without friction. When adding small friction (μ=0.06) the active force increased essentially. A similar effect was observed for the die pressure. The consequence of high forming force is just a bigger, more expensive press and use of special materials for tools [20].

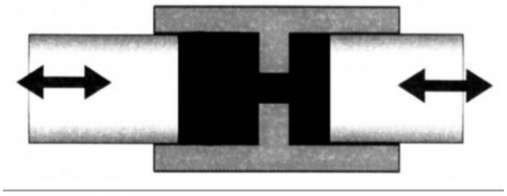

Figure 5. Schematic of reciprocating extrusion compression.

E.CYCLIC CLOSE DIE FORGING:

In 1988, Ghosh was granted a patent for three axes hot forging which could also be called cyclic close forging (CCDF). CCDF is a plane strain process in which a billet is compressed along its two or three axes as a result of one or two rotations between successive operations [21-22].

The equivalent plastic strain is

$\boldsymbol{\varepsilon}$= n 2/ $(3)^{1/2}$(ln (H/h))................... eq[4]

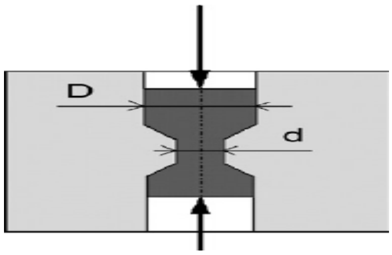

Figure 6. schematic of cyclic extrusion compression

F. REPETITIVE CORRUGATION AND STRAIGHTENING:

Repetitive corrugation and straightening(RCS) is a simple sever plastic deformation technique used to process sheet metals. In RCS, a sheet is pressed between two corrugated dies followed by pressing between two flat dies. RCS has gained wide popularity to produce the grained sheet metals[23].

It is demonstrated that the extrusion strain rate of RCS for aluminium alloy must be higher than the eutectoid reaction temperature of the alloy. After the alloy has more homogeneous fine grained structure than the as-received one and some equiaxed grains occur in some areas. Die fraction volume of the second face increases during the subsequent pass.

The probability of the contribution for number of pass and strain rate is 77.8% and 12.1%. The remaining parameters such as specimen thickness and combing effects of strain rate, number of pass and thickness is very less significant towards the response values.

The principle of repetitive corrugation and straightening process developed by Huang et al. is represented schematically in fig [7]. The technique consists of bending a straight billet with corrugated tools and then restoring the straight shape of the billet with flat tools. The equivalent strain per one operation is given by [24]

ε = 4ln [(r+t)/(r+0.5t)] / $[(3)^{1/2}]$ eq[5]

Where, t is the thickness of sample and r is the curvature of bent zone.

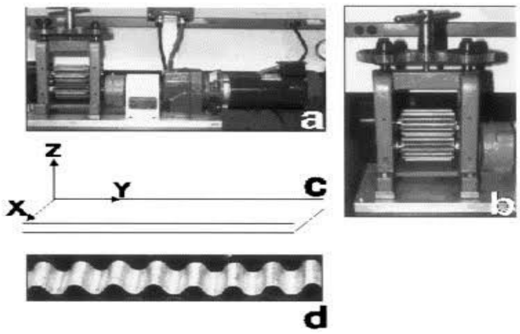

Figure 7. schematic of repetitive corrugation and straightening

G. SEVERE TORSION STRAINING:

The principle of the sever torsion straining(STS) process developed by Nakamura et al. is represented schematically fig[8].The process consists of producing a locally heated zone and creating torsion strain in the zone by rotating one end with the other. The rod is moved along the longitudinal axis while creating the local straining. Therefore, a severe plastic strain is produced continuously throughout the rod. In order to create the torsion strain efficiently, the locally heated zone should be narrow and the rotation of the rod should be fast with respect to the moving speed of the rod. Moreover, a modification is made for the cooling system so the heated zone is more localized to create torsion strain.[25-26].

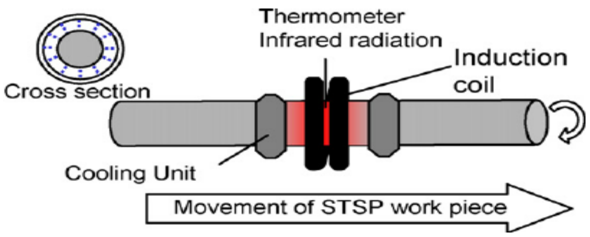

Figure 8. schematic of sever torsion straining.

H. SUPER SHORT MULTI- PASS ROLLING:

A new SSMR to produce ultra-fine grained hot strip is introduced, featuring: closely spaced rolling stands, continuous high speed rolling with moderately large reduction rolling, rapid inter pass cooling and rapid finish rolling cooling. An ultra-fine-grained CMn steel strip(1µm) is obtained with a 700 MPa yield stress. A proper choice of the work roll diameter and a careful control of the friction coefficient should make it possible to keep the rolling force at a level compatible with design capacity of a conventional rolling mill [27].

I. CYCLIC CHANNEL DIE COMPRESSION:

The CCDC is a special variant of the channel die compression process is used since several decades to simulate rolling. The geometries of specimen and the CCDC channel are in principal syntonized in that way, that the material flows only in direction of the channel at applied compressive load. The geometry of the specimen remains about equal before and after a processing step if initial height of the specimen and length of the channel are identical. Thus, it is possible to subject the same specimen several; times to the CCDC process by rotating the material by 90degree around the transverse direction (TD) of the channel(named 'route 1'). If the specimen has additionally a squared cross section a second CCDC processing route is possible that is given two consecutive rotations of each 90degrees; first around TD(like route 1) followed by a rotation around the normal direction(ND). This combination of materials rotation is named 'route 2'. The size of the structural elements is about the same after different types of SPD. It seems that structural elements after SPD by CCDC R1 and ECACE RC are more elongated than in the case of SPD by CCDCR2.

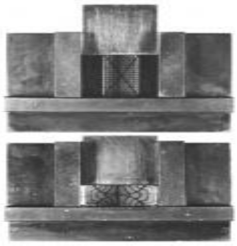

Figure 9. schematic of cyclic channel die compression

J. MECHANICAL ALLOYING:

Mechanical alloying/milling(MA/MM) is a solid state powder processing technique involving repeated cold welding fracturing and re welding of blended powder particles in a high- energy ball mil to produce a homogeneous material. Originally developed to produce oxide- dispersion strengthened (ODS) nickel - and iron - base super alloy for application in the aerospace industry,[28] MA has now been shown to be capable of synthesizing a variety of equilibrium and non-equilibrium alloy phases starting from blended elemental or pre-alloyed powders[29]. The non-equilibrium phases synthesized include supersaturated solid solutions, Meta stable crystalline and quasicrystalline phases, nanostructures and amorphous alloys. One consideration that should be avoided is powder contamination.

Mechanical alloying is akin to metal powder processing, where metals may be mixed to produce super alloys. Mechanical alloying occurs in three steps. First the alloy materials are combined in a ball mill and ground to a fine powder. A hot isolatic processing (HIP) process is then applied to simultaneously compress and sinter the powder. A final heat treatment existing internal stresses produced during any cold compation which may have been used. This produces an alloy suitable for high heat turbine blades and aerospace components.

Design parameters include type of mill, milling container, milling speed, milling time, type, size and size distribution of grinding medium. Ball-to-powder weight ratio, extent of filling the vial, milling atmosphere, process control agent, temperature of milling, and the reactivity of the species [30].

The process of mechanical alloying involves the production of a composite powder particles by:

1. Using a high energy mill to favor plastic deformation required for cold welding and reduce the process times.
2. Using a mixture of elemental and master alloy powders (the latter to reduce the activity of the element since it is known that the activity in an alloy or a compound could be orders of magnitude less than in a pure metal).
3. Eliminating the use of surface - active agents which would produce fine pyrophoric powder as well as contaminate the powder.
4. Relying on a constant interplay between welding and fracturing to yield a powder with a refined internal structure, typical of very fine powder normally produced, but having an overall particle size which was relatively coarse, and therefore stable.

During high-energy milling the powder particles are repeatedly flattened, cold welded, fractured and re-welded. Whenever two steel balls collide, some amount of powder is trapped in between them. Typically around 1000 particles with an aggregate weight of about 0.2 mg are trapped during each collision. The force of the impact plastically deforms the powder particles leading to work hardening and fracture. The new surfaces created enable the particles to weld together and this leads to an increase in particle size. Since in the early stages of milling, the particles are soft (if we are using ductile-ductile or ductile-brittle material combination), their tendency to weld together and form large particles is high. A broad range of particle sizes develops, with some as large as three times bigger than the starting articles. The composite particles at this stage have a characteristic layered structure consisting of various combinations of the starting constituents. With continued deformation, the particles get work hardened and fracture by a fatigue failure mechanism and/ or by the fragmentation or fragile flakes [31].

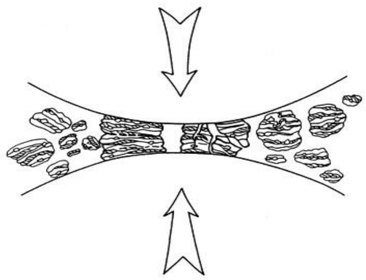

Figure 10. Schematic of mechanical alloying

K. ASYMMETRIC ROLLING:

In asymmetric rolling (ASR), a rolling mill is modified such that one roll has a higher velocity than the other. This is typically done with either independent speed control or by using rolls of different size. This creates a region in which the frictional forces on the top and bottom of the sheet being rolled are opposite, creating shear stress throughout the material in addition to the normal compressive stress from rolling. Unlike other SPD processes, ASR does not maintain the same net shape, but the effect on the microstructure of the materials is similar [32-36].

L. SURFACE TREATMENTS:

More recently, the principles behind SPD have been used to develop surface treatments that create a nanocrystalline layer on the surface of a material. In the surface mechanical attrition treatment (SMAT), an **ultrasonic horn** is connected to an ultrasonic (20 kHz transducer), with small **balls** on top of the horn. The work piece is mounted a small distance above the horn. The high frequency results in a large number of collisions between the balls and the surface, creating a **strain rate** on the order of 10^2-$10^3 s^{-1}$. The NC surface layer developed can be on the order of 50μm thick [37]. The process is similar to **shot peening**, nut the kinetic energy of the balls is much higher in SMAT[38].

An ultrasonic nanocrystalline surface modification (UNSM) technique is also one of the newly developed surface modification technique. In the UNSM process not only the static load, but also the dynamic load is exerted. The processing is conducted striking a work piece surface up to 20K or more times per second with shots of an attached ball to the horn in the range of 1K-100Kper square millimeter. The strikes, which can be described as cold-forging, introduce SPD to produce a NC surface layer by refining the coarse grains until nanometer scale without changing the chemical composition of a material which render the high strength and high ductility. This UNSM technique does not only improve the mechanical and tribological properties of a material, but also produces a corrugated structure having numerous of desired dimples on the treated surface [39].

III. CONCLUSION

Process of sever plastic deformation, defined as metal forming, process in which an ultra-large plastic strain was imposed on a bulk material in order to make ultra-fine grained metals, were reviewed in this keynote paper, As processes used for this purpose, various methods such as ARB, HPT, RCS, CEC, STS, CCDF, etc, were developed, and combined SPD processes with conventional processes were also proposed.

The properties of the metals processed by SPD are also reviewed. The SPD-processed metals have very high strength, and in order to increase the strength further, conventional cold forming processes are combined with SPD processes. Since the ductility of metals is reduced by relatively low strain, the heat treatment of annealing is conducted after the SPD process in order to improve the ductility. The properties of the metals processed by the SPD processes exhibit high strength and ductility that lead to good fatigue characteristics.

The UFG could be used as structural materials due to these properties, but the area of the application is limited at the moment because the available size of billet is small. Since SPD technology can convert all metals into UFG metals, it is expected that new methods of producing large billets will enlarge the area of applications.

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