Constrained bending and straightening-a proposed method for severe plastic deformation of metals

WM Mwita[1*], ET Akinlabi[2] and KO Sanusi[3]

[1,2,3]Department of Mechanical Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, PO BOX 524, APK 2006, Republic of South Africa.

*Corresponding author email address: mwita_wa@yahoo.com

Abstract. The use of severe plastic deformation (SPD) technology to process ultra-fine/nano grains metals with enhanced desired properties for structural and biomedical applications have shown good results. However, SPD technology is still limited to discrete processes, small size samples with inhomogeneous strain. This paper proposes a new method for severe plastic deformation of metals known as constrained bending and straightening (CBS). The method is aimed to provide continuous production of ultra-fine/nano grains metals with improved strain homogeneity. The CBS process analytical model and its working principle are presented, a constitutive relation of feed length, bend roller diameter, effective strain and tensile strength is established. Results show that the magnitude and homogeneity of induced effective strain and tensile strength increase with the decrease of both feed length and bending roller diameter. Effective strain increased by 200% from 6mm to 2mm feed lengths. At 2mm feed length, tensile stress increased from 1223.8 MPa at 1 pass to 1302.5 MPa at 4 pass. Results from this study promise that CBS technique is potential to be adapted for continuous SPD of bulky length metal sheets with enhanced homogeneous properties.

1. Introduction

Severe plastic processed metals have shown improvement in microstructure and mechanical properties such as ultrafine /nano grain size, high static and fatigue strengths, increased hardness, wear, corrosion resistance and biocompatibility [1,2,3]. In a true SPD, material is subjected to a hydrostatic stress state with accumulation of both plastic strains and crystal lattice dislocations. The pinned movement of dislocations results to increase of grain boundaries hence transformation from coarse grains (grain size equal or higher than 1000 nm) to fine grains (grain size less than 1000 nm). [4,5]. Currently, the major successful SPD processes reported in the literature are high pressure torsion (HPT), equal channel angular pressing (ECAP), asymmetric rolling (AR), accumulative roll bonding (ARB) and repetitive corrugation and straightening (RCS) [6,7,8]. Discontinuous operation, limited size and geometry of processed samples have been the major challenges to most of these processes [9]. Improved models with better results for HPT and ECAP techniques for continuous and larger sample size process were reported, these include Continuous-HPT [10], Incremental-HPT [11], Incremental-ECAP [12,13] and ECAP-Conform [14]. Based on simplicity and the rolling facility required, AR and ARB are viable for continuous process of large size samples, but they are limited to process sheets samples of rectangular cross section[15,16]. Inhomogeneity of induced strain and other enhanced properties in the processed samples has also been a serious drawback of the SPD processes. For instance significant strain inhomogeneity has been observed in processed samples with HPT [17,18] and RCS [19,20]. RCS is the process where plastic simple shear bending strain is induced in material via repeated corrugation and straightening.

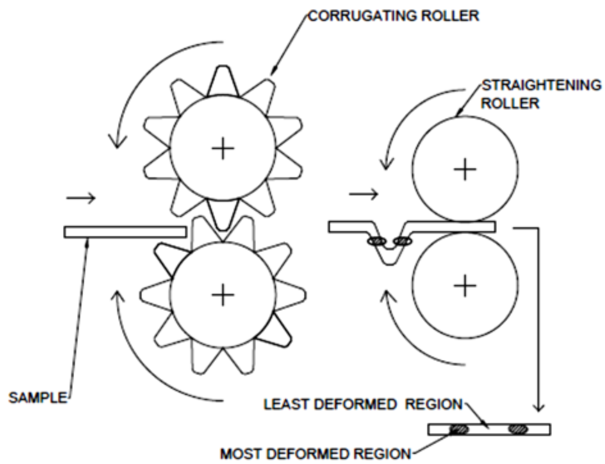

Figure1. Corrugated and straightened sample in a continuous process tool

A continuous RCS process is represented in figure1. A deformed sample is shown in both corrugated and straightened states. In the corrugated state, the inclined planes (shaded regions) are the most deformed parts while the horizontal planes (un-shaded regions) are the least or non-deformed parts. During straightening back to flat state, additional strain is induced to the inclined planes while the horizontal planes remaining relatively un-deformed. Deformation inhomogeneity due to un-even distribution of strain paths remains in material even after several RCS passes. RCS related discontinuous processes such as RCS-Rolling [21], constrained groove pressing (CGP) [22,23] and constrained groove pressing-cross rotation (CGP-CR) [24,25] were developed with some improvement of strain homogeneity in the processed samples. It is concluded that more research is required before successful implementation of SPD technology to continuous bulk production of ultra-fine/ nano metals with homogeneous properties. In this paper a novel method of CBS for SPD of metals is introduced. The CBS process is aimed to improve the strain homogeneity and provide continuously process of ultra-fine/nano grain metals with enhanced desired microstructure and mechanical properties. A detail discussion of CBS process on its working principle and analytical model results are presented in the forthcoming chapter 2.

2. Constrained bending and straightening

CBS involves bending and straightening of the constrained material sample followed by feeding of the sample at a selected feed length, the process is repeated over the entire length of the sample. The working principle of CBS is represented in figure 2(a). It consists of the bending roller B, straightening roller S, constraining bars C and the feed system, F. One pass of CBS is completed when the process is performed on the entire length of the sample at a specified feed length. The direction of motion of the sample is perpendicular to that of both bending and straightening rollers. To avoid excessive induced plastic strain the maximum bend height on the sample should not exceed the radius of the bending roller.

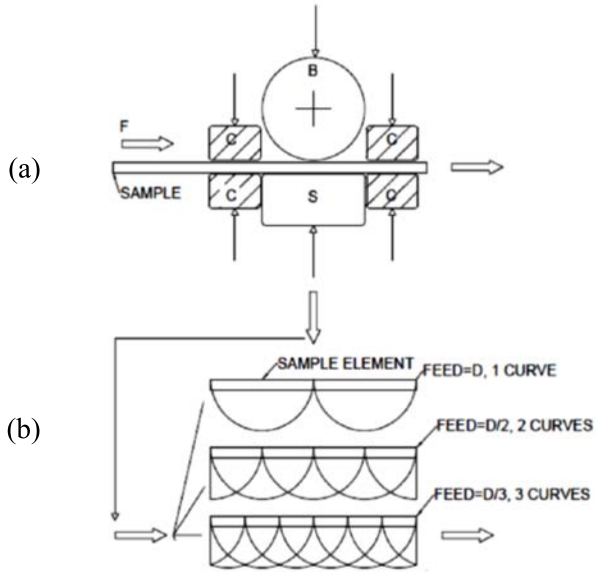

Figure 2. (a) Principle of CBS (b) Feed length and respective bending curves in CBS

Table1. (a) CBS tool parameters, (b) Ti6Al4V alloy material properties.

(a)		(b)	
Bending roller Diameter, D (mm)	6	ASTM B265, Grade5 Chemical composition: C(0.02), Fe(0.12), N(0.018,) O(0.1), H(0.003), Al(5.9),V(4.1), Others(<0.4) and Ti(balance).	
Feed lengths, F(mm)	2, 3, 6	Yield strength, S_Y (MPa)	Max 886
		Tensile strength, S_{UTS} (MPa)	Max 950
		% Elongation	10-13
Number of passes, N	1, 2, 3,4	Dimensions (LxWxT)(mm)	153x41x2

During feeding, the sample-constraining bars contact forces should be minimized as much as possible to reduce friction and feed forces. The magnitude of feed length in a complete pass determines the number of bending curves induced in the sample, ultimately the magnitude and homogeneity of the induced strain. Figure 2(b) shows a longitudinal element of length 2D imaginary cut from the sample processed with a bending roller of diameter D. The figure also shows the number of induced bending curves in the element at feed lengths D, D/2 and D/3. It is shown that decreasing feed length F, relative to bending roller diameter D increases the number of bending curves and overlapping per pass, hence increasing magnitude and homogeneity of the induced strain. Using the Von Mises (Maximum Distortion Energy) failure criterion, the effective strain for a sheet sample bent with semi-circular die (roller) and straightened can be given by equation (1) in [26] as:

$$\varepsilon_{eff} = N\frac{4}{\sqrt{3}}\ln\left(\frac{R+T}{R+0.5T}\right) \qquad (1)$$

R = surface radius of the bending roller =D/2 , T = thickness of sample and N = number of passes. Introducing to equation (1) the number of plastic bending curves per pass, M, where M=D/F=2R/F, F= feed length, 0<F<=2R, the effective strain for a sample performed with CBS is given in equation (2) as:

$$\varepsilon_{eff} = N\frac{2R}{F}\frac{4}{\sqrt{3}}\ln\left(\frac{R+T}{R+0.5T}\right) = N\frac{R}{F}\frac{8}{\sqrt{3}}\ln\left(\frac{R+T}{R+0.5T}\right) \quad (2)$$

The strength of material due to strain hardening effect is determined using the power law equation (3) as;

$$S = K\varepsilon_{eff}^{n} \quad (3)$$

S = tensile strength-true stress, ε_{eff} = total effective plastic strain, K= strength coefficient, n = strain hardening exponent. A CBS model presented in figure 2 was analytically evaluated on Ti6Al4V titanium alloy at room temperature. For Ti6Al4V alloy, K= 1200 MPa and n = 0.045 [27]. CBS tool design parameters and titanium alloy material properties are presented in table1. For each of feed lengths (F=2mm, 3mm and 6mm) and passes (N=1, 2, 3, 4), magnitudes of induced effective strain and tensile stress were determined using equations (2) and (3) respectively. Analytical results are presented in figure 3.

3. Discussion of results

Results presented in figure 3(a) show that the effective plastic strain increases with the decrease of feed length and the increase of number of passes. In each pass, decreasing the feed length from 6mm to 2mm increases the effective strain by 200%. The effective strain at pass (N=4) is 300% higher than that at pass (N=1). An increase of effective strain is attributed by increased number of deformation curves/strain in samples under CBS process at low feed length. Equation (2) shows that effective strain increases with the decrease of bending roller radius, therefore the smaller radius bending roller is more effective for plastic shear bending deformation.

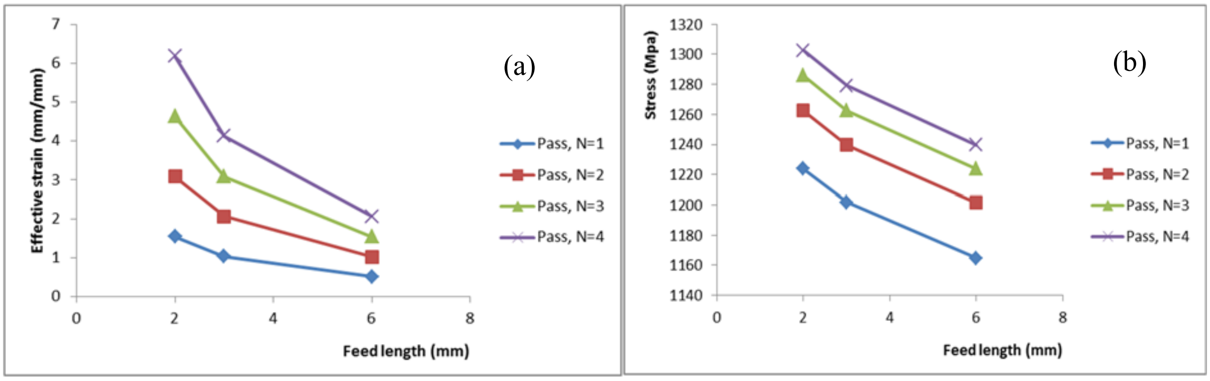

Figure 3. (a) Effective strain vs feed length (b) Tensile true stress vs feed length.

Results presented in figure 3(b) reveal that in each pass the tensile stress at 2mm feed is higher than that at 3mm and 6mm feeds respectively. At 2mm feed length, stress increased significantly from 1223.8 MPa at pass (N=1) to 1262.5 MPa at pass (N=2). The stress increased slightly to 1285.7 MPa at pass (N=3) and 1302.6 at pass (N=4). Significant increase of stress was attributed by strain hardening strengthening due higher induced plastic strain in material. The reason for slight increase of stress at 3 and 4 passes is saturation of material strain hardening and initiation of material yielding.

4. Conclusion

In this work, constrained bending and straightening (CBS) technique capable of continuous SPD of metals of bulky lengths, with improved homogeneous properties was introduced. CBS analytical model has shown promising results. The magnitude and homogeneity of induced effective strain and strength increase with the decrease of both feed length and bending roller diameter. The CBS technique was specifically proposed to process rectangular section (sheets) samples. However the same technique can be adapted to process round section samples by simply replacing rectangular section bending roller with the appropriate round section bending die. The future work is to design, fabricate and test a physical model for this process.

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