Effects of Severe Plastic Bulk and Surface Deformations on Fatigue Performance of cp-Cu

H. M. S. Sin[1], M. Janecek[2], M. Wollmann[1] and L. Wagner[1]

1 Institute of Materials Science and Engineering, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany
2 Department of Metal Physics, Charles University Prague, Praha, Czech Republic

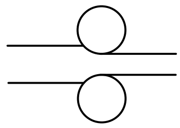
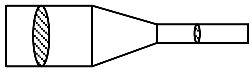
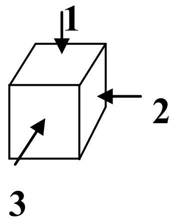
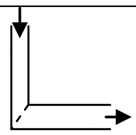
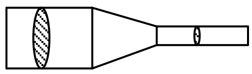
Abstract
The effect of severe plastic surface deformations by shot peening (SP) and ball-burnishing (BB) on high cycle fatigue (HCF) performance of commercially pure (cp) -Cu is compared with that after ambient temperature plastic bulk deformation caused by rotary swaging (SW), equal channel angular pressing (ECAP) and wire-drawing (WD). It is shown that shot peening (SP) and ball-burnishing (BB) result in near-surface microstructures very similar to those after severe plastic bulk deformations. Accordingly, high-cycle fatigue (HCF) performance which is dominated by surface and near-surface properties is much improved by SP and BB and hardly different from that after severe plastic bulk deformation. As opposed to the observed microstructural refinements and work-hardening, residual compressive stresses as also induced by SP and BB are of minor importance in HCF of cp-Cu.

Keywords: Cp-Cu, severe plastic deformation, grain refinement, micro-hardness, fatigue performance

Introduction
Severe plastic bulk deformations of coarse grained materials by methods such as high pressure torsion (HPT), alternative roll bonding (ARB), SW or ECAP are known to refine the grain size of a number of materials such as Cu [1], Al [2] and Mg [3] and their alloys to values well below 1 μm. This grain refinement can lead to drastic increases in yield stress, tensile strength and high cycle fatigue (HCF) strength. In previous work on an α-brass and an austenitic stainless steel [4], both shot peening and ball-burnishing were observed to induce very high degrees of local plastic deformations and concomitant hardness increases in near-surface regions. Maximum deformation degrees were estimated to be of the order of $\varphi \geq 1$ and thus, comparable to typical deformations applied via methods of severe plastic bulk deformation such as ECAP or SW or 3-dimensional pressing (3-DP). In order to find out if the near-surface severe plastic deformation as typically induced by SP and BB is the main reason for the observed improvement in fatigue performance relative to the un-deformed coarse grained reference, the present work was undertaken to compare the fatigue performance of cp-Cu after severe plastic surface to that after severe plastic bulk deformations. Such a comparison will also shed some light on possible additional effects of residual compressive stresses on fatigue performance of cp-Cu in case of SP and BB.

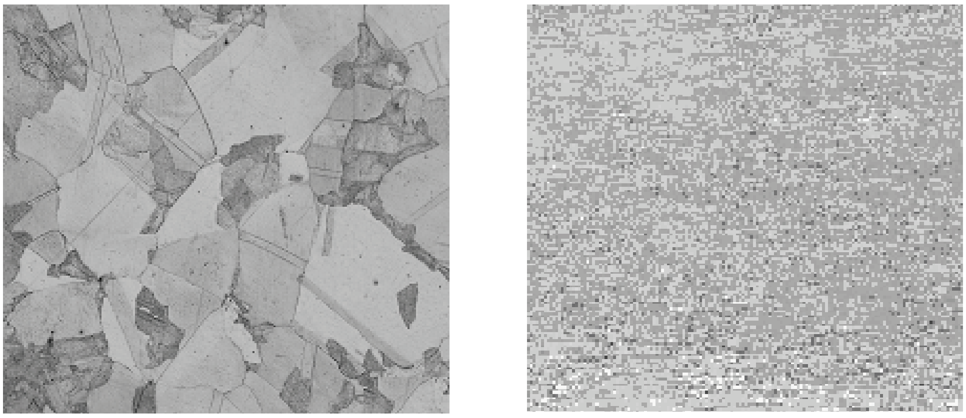
Experimental Methods
Cp-Cu material was used in the present investigation because it can easily be plastically deformed at ambient temperature due to its face-centred-cubic (fcc) crystal structure, low strength and high ductility. The as-received shapes had either square (10 x 10mm) or circular cross sections (∅ 30mm). All material was given an annealing treatment at 450 °C for 2 hours.
The various methods of bulk deformation used in the present investigation are schematically shown in Table 1 together with the definition of the true deformation degree.

Table1. Methods applied in bulk deformation

Process	Schematic drawing	Deformation degree
Uni-directional rolling (UR)		$\varphi_t = \ln (h_o/h)$
Rotary swaging (SW)		$\varphi_t = \ln (A_o/A)$
3-dimensional pressing (3-DP)		$\varphi_t = \Sigma\ \varphi_1 + \Sigma\ \varphi_2 + \Sigma\ \varphi_3$
Equal channel angular pressing (ECAP)		$\varphi_t = \Sigma\ \varphi_i$
Wire- drawing (WD)		$\varphi_t = \ln (A_o/A)$

The microstructures before and after bulk deformation were characterized by optical microscopy (LM), transmission electron microscopy (TEM) and X-ray diffraction (XRD). Mechanical properties were determined by hardness measurements, tensile and fatigue testing. Tensile tests were performed on either flat or cylindrical specimens having gage lengths of 20mm. The initial strain rate was 8.3 x 10^{-4} s^{-1}. Ambient temperature fatigue tests were performed in rotating beam loading (R = -1) on hour-glass shaped electrolytically polished specimens at a frequency of 50Hz in air. In addition to the various severe plastically deformed conditions, the as-received annealed condition was tested as reference.
SP was done using SCCW14 having an average shot size of 0.35mm. Peening was done to full coverage at various Almen intensities.
BB was performed by means of a conventionally lathe by using a hydrostatically driven tool from Ecoroll AG, Celle, Germany and a hard metal ball of ∅ 6mm (HG6). The burnishing pressure was widely varied
Micro-hardness-depth profiles were determined on cross sections. Residual stresses were determined by the incremental hole drilling method.

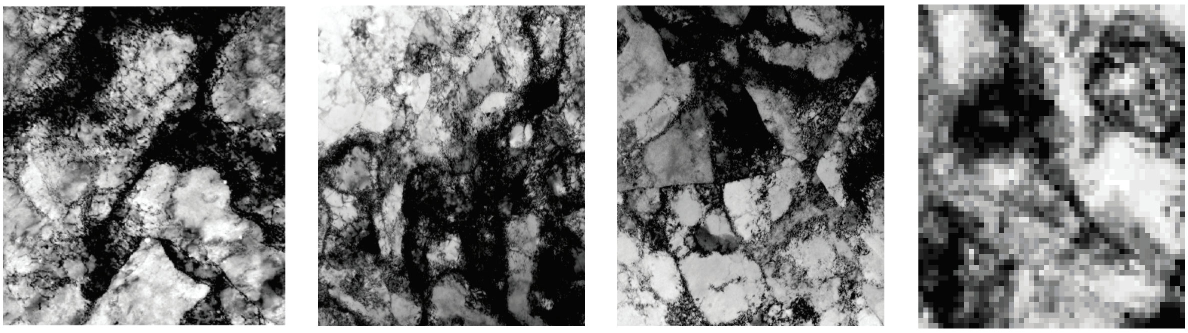
Experimental Results and Discussion
Examples of the changes in microstructure caused by the various methods of severe plastic deformation are illustrated in Figure 1. Starting with the as-received condition having a grain size of about 300μm (Fig. 1a), the grain sizes are drastically reduced by the various deformation methods provided that the utilized deformation degrees were high enough. As a typical example, the fine-grained microstructure as observed after UR (φ = 2.3) is illustrated in Figure 1b.



a) AR 100 μm b) UR (φ = 2.3) 20 μm

Figure 1: LM Microstructures

In addition to optical microscopy, TEM was used to resolve the microstructures much refined due to severe plastic deformation (Fig. 2). As seen in Figure 2, the average grain size is of the order of 0.5μm.

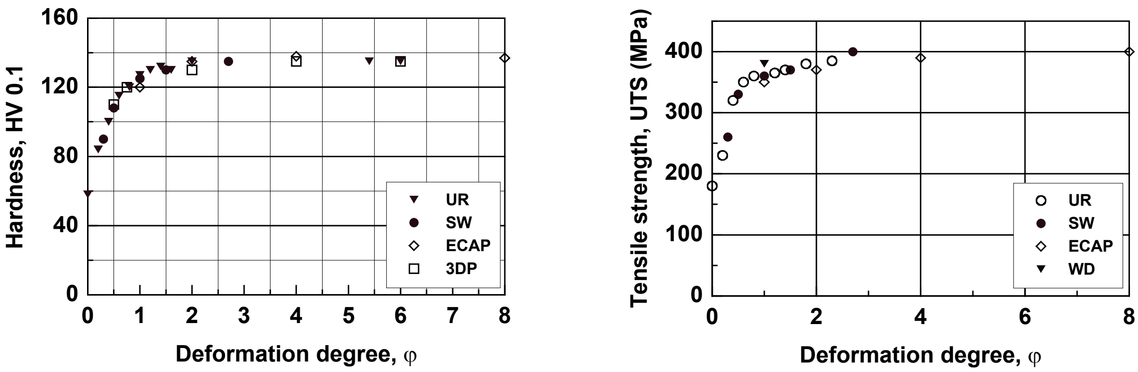


a) 3-DP (φ = 4) b) SW (φ = 2.6) c) WD (φ = 1.2) d) ECAP (φ = 4)

400 nm

Figure 2: TEM Microstructures

The influence of the degree of cold deformation on the bulk hardness and tensile strength values of the various conditions are shown in Figure 3. Both hardness and tensile strength values strongly go up with increasing deformation degree and then level off at maximum values of about 130 to 140 HV0.1 at deformation degrees of about φ = 1 to 2.



a) HV vs. φ b) UTS vs. φ

Figure 3: Effect of degree of cold work on bulk properties

Obviously, the measured hardness values are independent of the particular deformation method used and only depend on the degree of deformation as described in [5].
Varying the process parameters Almen intensity and burnishing pressure, most marked fatigue life improvements at constant stress amplitudes were observed by using 0.18mmA Almen intensity and 150bar burnishing pressure for SP and BB, respectively. Further testing was done only on these optimum conditions.
Micro-hardness values of AR after both SP (0.18mmA) and BB (p = 150bar) as a function of distance from the surface are illustrated in Figure 4.

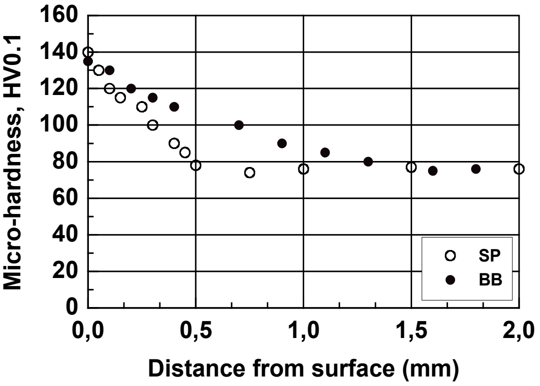


Figure 4: Micro-hardness-depth profiles

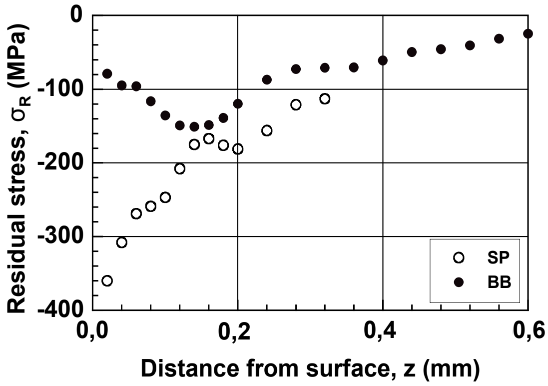


Figure 5: Residual stress-depth profile (SP)

Interestingly, the maximum hardness values at the surface are very similar to those measured after severe plastic bulk deformation (compare Fig. 4 with Fig. 3a). Starting with these high values, the hardness values of SP and BB gradually decrease with distance from the surface. The base hardness is reached at depths of 500μm and 1500μm for SP and BB, respectively.
The residual stress-depth profile of both SP and BB is shown in Figure 5. Marked residual compressive stresses were observed at the surface after SP with a gradual decrease into the interior. The magnitude of the maximum value close to the surface (380 MPa) is as high as the UTS values measured after severe plastic bulk deformation (compare Fig. 5 with Fig. 3b). Residual compressive stresses after BB were much lower, this being caused by the ball size in BB amounting to 6mm as opposed to 0.35mm in SP.
The S-N curves of the plastically bulk deformed condition SW and the reference condition AR are compared in Figure 6.

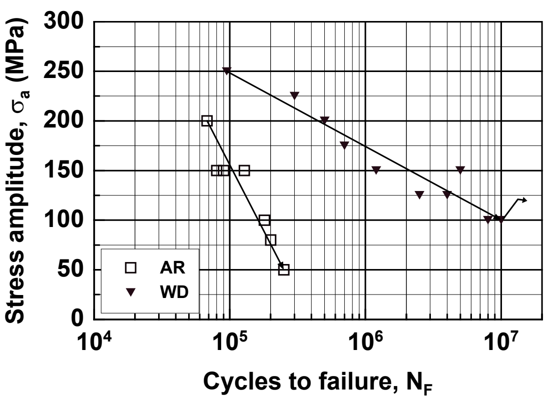


Figure 6: S-N curves: Effect of plastic condition AR

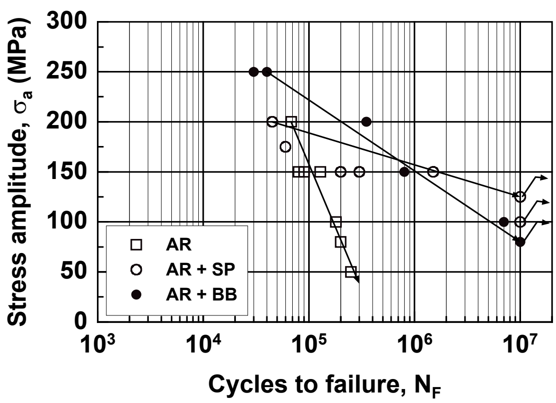


Figure 7: S-N curves: Effect of SP and BB on bulk deformation

Compared to the reference AR, severe plastic bulk deformation by WD leads to marked fatigue life improvements, in particular, in the HCF regime.
The S-N curves after optimum mechanical surface treating of AR are illustrated in Figure 7.
Fatigue life improvements due to BB are somewhat superior to those caused by SP at stress amplitudes above 150 MPa while at stress amplitudes below 150 MPa, SP is clearly superior to BB (Fig. 7). Presumably, the latter effect is due to much higher near-surface residual compressive stresses in SP (Fig. 5b). On average, both mechanical surface treatments improve the fatigue performance of AR very similar as observed after severe plastic bulk deformation by means of WD (compare Figure 7 with Figure 6).
In order to find out if mechanical surface treatments can further improve the fatigue performance of cp-Cu already severe plastically bulk deformed, fatigue tests were done on SP and BB of WD. Results are shown in Figure 8.

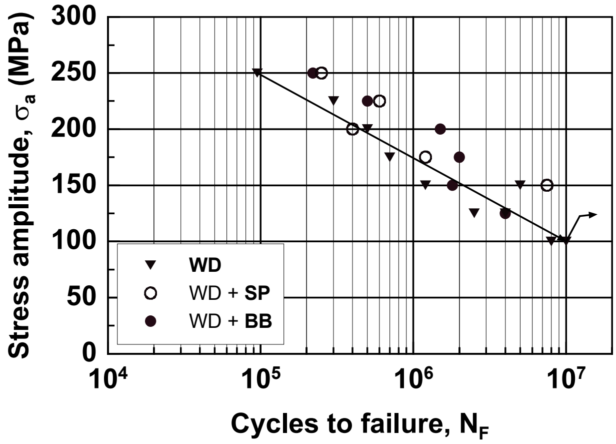


Figure 8: S-N curves: Effect of SP and BB on condition WD

As seen neither SP nor BB was able to significantly improve the excellent fatigue performance of the severe plastically bulk deformed condition WD. This indicates that in conditions being highly strengthened by cold work no further surface strengthening caused by mechanical surface treatments is likely.

Conclusions
Severe plastic bulk deformation by means of UR, 3-DP, SW, ECAP and WD leads to both drastic work hardening and grain refinements in cp-Cu. Hardness and tensile strength values strongly increase with increasing deformation degree and then saturate at $\varphi \geq$ 1-2. The saturation values in hardness and tensile strength hardly depend on the particular deformation method applied. SP and BB result in near-surface maximum hardness values comparable to those observed after severe plastic bulk deformation. This indicates that microstructural changes in the near-surface due to SP and BB are similar to those in severe plastic bulk deformation.
Since HCF performance mainly depends on surface and near-surface properties, it does not make any difference if the severe plastic deformation is applied to the bulk material or only to the surface of the specimens. Obviously, residual compressive stresses which are also induced by mechanical surface treatments do not further improve the HCF strength. Presumably, these stresses are not cyclically stable in cp-Cu.

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References

[1] W. Wei, K. X. Wei, Q. N. Shi; *Grain refinement of copper sheets through accumulative roll-bonding process at room temperature*, Ultrafine Grained Materials IV (Y. T. Zhu, T. G. Langdon, Z. Horita, M. J. Zehetbauer, S. L. Semiatin, T. C. Lowe, eds.) TMS (2006) pp 209.
[2] A. P. Zhilyaev, K. Oh-ishi, G. I. Raab and T. R. McNelley, *Influence of processing parameters on texture and microstructure in ECAPed aluminum*, Ultrafine Grained Materials IV (Y. T. Zhu, T. G. Langdon, Z. Horita, M. J. Zehetbauer, S. L. Semiatin, T. C. Lowe, eds.) TMS (2006) pp 113.
[3] J. Müller, S. Yi, M. Janecek, J. Cizek and L. Wagner, *Effect of equal channel angular pressing on microstructure, texture and high-cycle fatigue performance of wrought magnesium alloys*, Int. J. Mat. Res. 100 (2009) pp 838.
[4] S.Yi, M. Wollmann, T. Ludian and L. Wagner, *Analyzing the near-surface deformation gradients due to shot peening and ball-burnishing of alpha brass and stainless steel*, ICSP 10 (K. Tosha, eds.), ACMUTJ (2008), pp 169.
[5] H. M. S. Sin, *Nano/ultrafine grained copper produced by various methods of severe plastic deformation*, Dr.-Ing. dissertation, TU Clausthal (2010).