COBEM-2017-2364
A STUDY ON THE INFLUENCE OF ECAP DIE DESIGN AND BACKPRESSURE ON THE DEFORMATION AND MECHANICAL PROPERTIES OF A SAE 1045 STEEL

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Abstract. *Equal channel angular pressing of metals have been studied extensively in the last decades for obtaining ultrafine grained metals and optimized properties. Many designs of ECAP dies were developed for processing different materials. This work focused on the investigation of the influence of the die design and backpressure on the deformation and mechanical properties of a SAE 1045 steel. A sliding bottom die and a conventional die were compared. Results indicated that both dies were efficient in producing heavily deformed, thus, hard materials. Conventional optical microscopy and scanning electron microscopy (SEM) revealed an oriented structure of ferritic grains and fractured or bent pearlite colonies. Stress-displacement curves indicated that sliding bottom die processing required a lower punch pressure, however, similar properties may be obtained in both dies. The results denote that sliding bottom dies may ease the processing of this steel.*

Keywords: *equal channel angular pressing, severe plastic deformation, die design.*

1. INTRODUCTION

Severe Plastic deformation (SPD) of metals have attracted interest of researches, since bulk ultrafine grained (UFG) metals can be obtained (Valiev and Islamgaliev, 2000) . Many SPD techniques were developed, as high-pressure torsion (HPT), accumulative roll-bonding (ARB), and, especially, equal channel angular pressing (ECAP) (Valiev and Langdon, 2006). Once high pressure is needed for ECAP of metals, many die configurations were developed along the last two decades for improving the workability of metals (Valiev and Langdon, 2006; Segal, 2004). Dies with sliding walls were developed in order to decrease punch pressure and pressure on die walls (Segal, 2004).

SPD deformation of pearlitic steels was studied previously by many authors. In one of the first works on this issue (Shin, *et al.,* 2002), researchers processed low carbon steels by ECAP and obtained highly refined ferritic grains and a great improvement in mechanical properties. The researchers observed that room temperature ECAP possibly led to carbon dissolution from cementite, increasing matrix strength. Also, ultrafine nanoparticles of cementite were formed during subsequent annealing, due to the supersaturated ferritic matrix.

Although ferritic matrix strength plays an important role, pearlitic structure and carbides also have high influence on steel strength. The pearlite strength derives from its laminar structure, with ductile ferrite and hard cementite. Many properties are based on pearlite interlamellar spacing and thickness. As an example, tensile strength of carbon steels increases, linearly, as lamellar spacing is decreased. It is known that pearlite lamellar spacing may be reduced by cold working (Li and Virta, 2011).

Authors (Vedani, *et al.,*2006) have studied the behavior of pearlite during SPD. It was observed that plastic deformation may fracture the lamellar structure in fine fragments after many ECAP passes. Severe Plastic Torsional

Straining of a high carbon (1,2 wt%), on the other hand, was able to produce an extremely disperse structure, with completely fragmentation and dissolution of cementite, leading to a supersaturated solid solution of carbon in the ferritic matrix (Korznikov, *et al.*, 1994).

In this work, deformation, microstruture and mechanical properties of a ferritic steel subjected to ECAP on different die designs was investigated. The influence of the application of backpressure was also studied.

2. EXPERIMENTAL PROCEDURE

Billets of a carbon steel (SAE 1045) were processed by ECAP at room temperature in two different dies: A conventional die and a sliding bottom die (as presented in Fig. 1), both with channel angle (Φ) of 120°. Samples were processed with and without backpressure in both dies, where the first billet applied the backpressure over the second. Pressing speed was kept at 1 mm.min^{-1} to avoid substantial heating of the billets (Yamaguchi, *et al.*, 1999). MoS$_2$ was used as lubricant media.

Processed samples were initially characterized by conventional metallography, SEM, Vickers hardness and pressure-stroke curves.

Metallographic preparation was performed by sandpaper grinding until #1500 and polishing with 3 µm and 1 µm diamond paste. Nital 2% was used as chemical etching.

Vickers hardness was made in the center, top and bottom surfaces of the samples, in order to evaluate the effect of friction of die walls on the hardness of the material.

Samples were designated as: As received (AR), conventional die processed without backpressure (CD1), conventional die processed with backpressure (CD2), Sliding bottom die processed without backpressure (SB1) and sliding bottom die processed with backpressure (SB2).

Figure 1: Sliding bottom (SB) and conventional die (CD) used for ECAP processing.

3. RESULTS AND DISCUSSION

3.1. Pressing of The Samples

ECAP was performed, as described, and Pressure-Stroke curves were acquired. Figure 2 presents the pressure profiles for all extrusions.
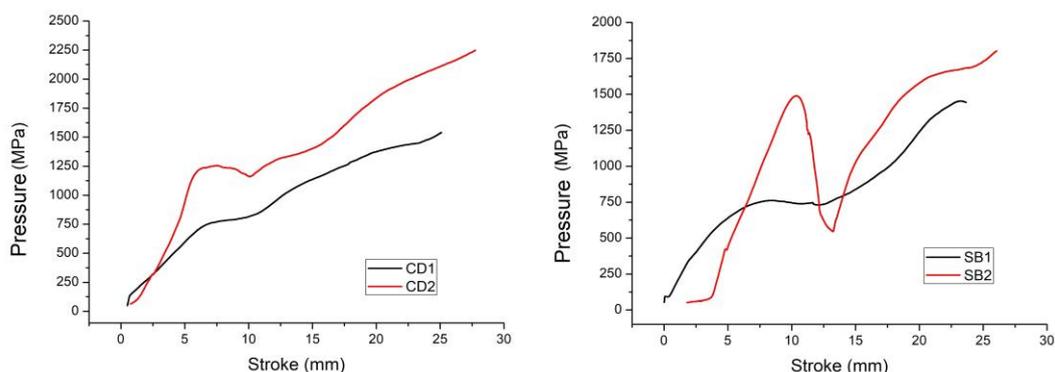

Figure 2: Pressure-Stroke curves for CD1 and CD2 samples (left) and, SB1 and SB2 samples (right).

Processing in conventional and sliding bottom dies led to a markedly different behaviour. Processing of CD1 sample showed an almost linear stress increase, whereas CD2 sample presented an initial great increase in pressure, due to the backpressue, and a second stage, where only the friction of the CD2 sample was active. . This curve shape in CD2 may possibly be associated to the friction reduction due to the beginning of the ejection of the first billet. Naturally, backpressure led to an increase in stress required for processing of CD2 samples.

SB1 sample presented a similar behavior during pressing, with stress increase during processing, however, this increase was not linear, but sigmoidal. SB2, on the other hand, presented a different behavior, with rapid increase and a subtle decrease in stress, which was possibly associated to an initial sliding of the bottom surface of the die, and the beginning of the ejection of the first billet, which momentarily relieved the stress during processing. When a steady state of sliding is achieved, punch stress starts to increase again until a stress behavior similar to SB1 is achieved.

3.2. Microstructural Analysis

After processing, all samples were characterized by conventional metallography in optical microscope. Figures 3, 4 and 5 shows the microstructure of AR, CD1 and CD2, SB1 and SB2 samples, respectively. All images were obtained in the middle section of the samples.
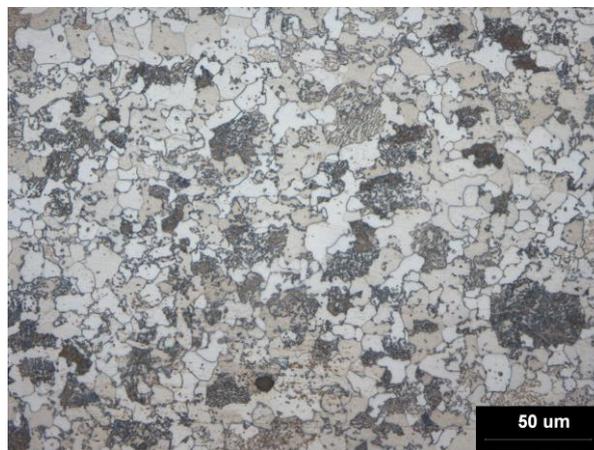

Figure 3: As received sample of SAE 1045 steel. Original magnification of 500x.
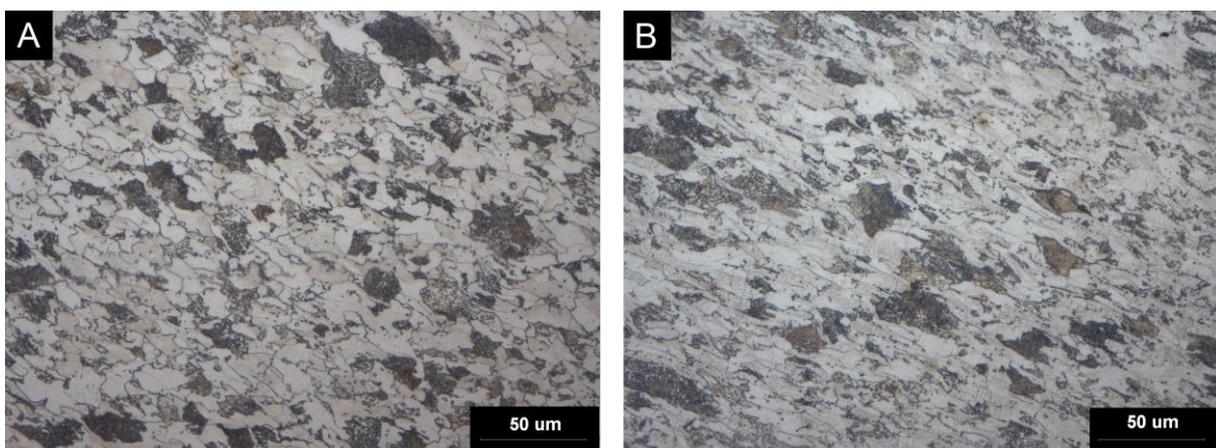

Figure 4: CD1 (A) and CD2 (B) samples. Original magnification of 500x.

As Fig. 3 shows, a usual microstructure of a 1045 steel, with a ferritic matrix and pearlite colonies. After processing (Fig. 4 and 5), some degree of grain orientation, due to simple shear plastic deformation of ECAP, can be observed.

In Fig. 4, it can be observed that MC2 sample presents highly oriented grains, indicating that the deformation on the conventional die was possibly more severe that in the sliding bottom die. Quantitative measurements on grain size were not performed, however, visual analysis indicate that MC2 sample presented substantial grain refinement, as reported in literature (Iwahashi, *et al.,* 1998).
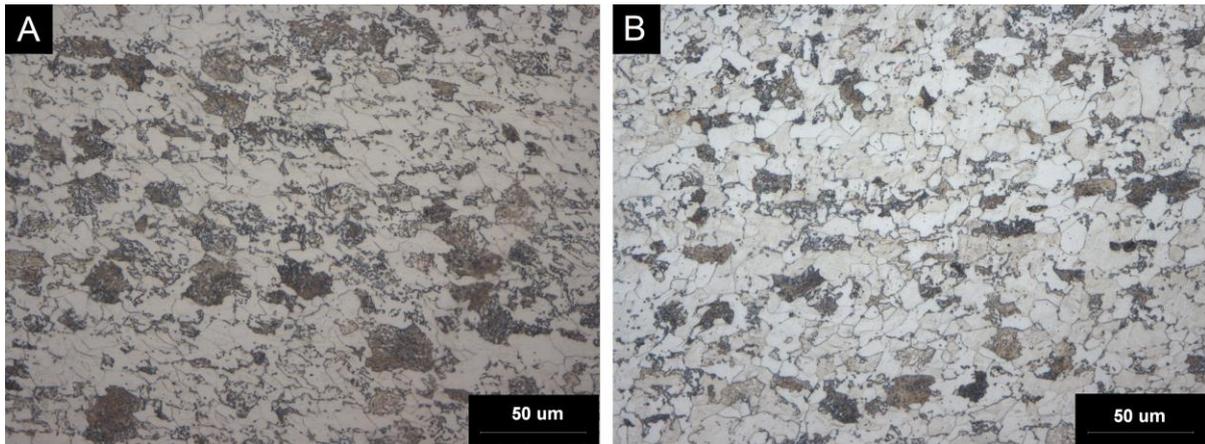
Figure 5: SB1 (A) and SB2 (B) samples. Original Magnification of 500x.

3.3. Hardness Tests

Hardness data of all samples is presented in Table 1.

Table 1: Hardness values for AR, MC1, MC2, SB1 and SB2 samples. Measures were performed in the middle section and top and bottom surfaces.

Hardness (HV)			
	As received		
(AR)	163.3 ± 3,1		
	Conventional die		
	Top surface	**Middle section**	**Bottom surface**
Without backpressure (MC1)	266.4 ± 7.9	242.8 ± 6.3	256.4 ± 8.3
With backpressure (MC2)	366.1 ± 21.5	285.8 ± 12.5	280.1 ± 7.7
	Sliding bottom die		
	Top surface	**Middle section**	**Bottom surface**
Without backpressure (SB1)	320.4 ± 26.4	230.2 ± 8.8	272,3 ± 10.6
With backpressure (SB2)	287.1 ± 7.5	257.2 ± 14.4	250.4 ± 12.3

AR sample presented usual hardness value for annealed 1045 steel. All samples processed by ECAP presented substantial increase in hardness, however, this increase was not homogeneous in all surfaces. MC1 sample hardness distribution indicates that work hardening in this experimental condition is reasonably homogeneous, although, hardness was slightly higher in the top and bottom surfaces, mainly due to friction in die walls. On the other hand, MC2 sample presented an inhomogeneous distribution of hardness, with very high hardness in the top surface of the sample. The greater work hardening in this condition is possibly associated to the volumetric restriction imposed by the first billet, which may increase the friction between the top surface of the sample and the die.In the sliding bottom die, SB1 presented a very inhomogeneous hardness distribution, with a softer middle section, harder bottom surface and much harder top surface. Apparently, although friction was alleviated in the bottom surface, as literature suggests (Segal, 2004), friction between the top surface of the sample and the die wall seems to play an important role on the hardening of this surface when backpressure was not applied.In SB2 sample, when backpressure was applied, the hardness distribution became much more homogeneous along the sample, however, top surface kept higher hardness values. The lower hardness in the middle section and bottom surface were expected, according to literature (Xu and Langdon,

2007). To improve hardness homogeneity along the samples, additional passes and the rotation of the sample would be necessary (Xu and Langdon, 2007).

3.4. SEM Analysis

To analyse the microstructure of the material thoroughly, specially the pearlite colonies, SEM analysis was performed in all samples.
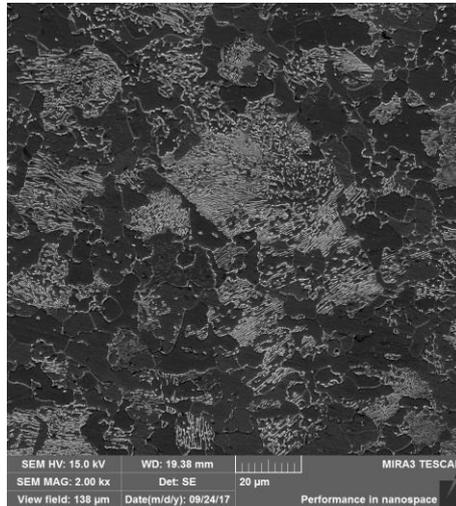

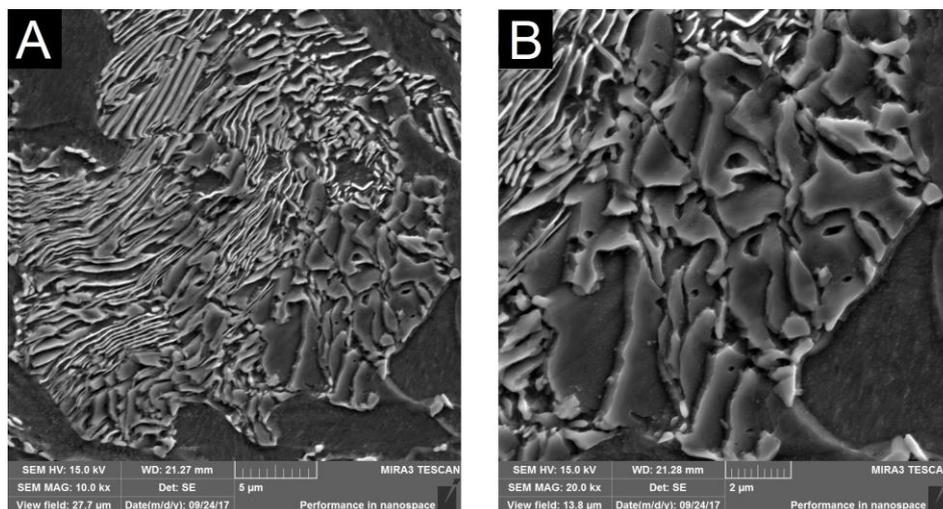Figure 6: Pearlite colonies in the AR sample.

Figure 7: Pearlite colonies in CD1 sample.

Pearlite behaviour under cold rolling was studied previously (Furuhara, *et al.,* 2005) and authors identified three different behaviours: irregular bent lamellae (IBL), coarse lamellae with shear band (CLS) and fine lamellae (FL). In IBL, the alignment of the lamellae changes with deformation, without fracture. CLS areas consist in areas with coarse interlamellar spacing and shear bands. FL are highly oriented areas with fine interlamellar spacing. These different behaviours were identified when different degrees of reduction were applied in steel. Images obtained for CD1 sample present some distortion and fracture in the pearlite colonies as Fig. 7 shows. Apparently, this behaviour of pearlite deformation is much similar to the IBL and FL reported previously.

On the other hand, Fig. 8 shows pearlite colonies deformed in bands, leading to heavy bending of pearlite lamellae. This morphology is alike CLS and FL. Figure 9 shows, differently, aligned (FL) and repeatedly fractured cementite lamella. In Fig. 9 (B) it can be observed some black spots where fracture occurred on cementite and a small hole was formed due to preferential chemical etching. SB2 sample also presented FL and fractured lamellae, as Fig. 10 shows. In all samples, the pearlite morphology was rather modified after ECAP. The relation between the orientation of pearlite

lamellae, ferritic matrix and ECAP shear deformation needs to be further discussed to explain the formation of these different morphologies.
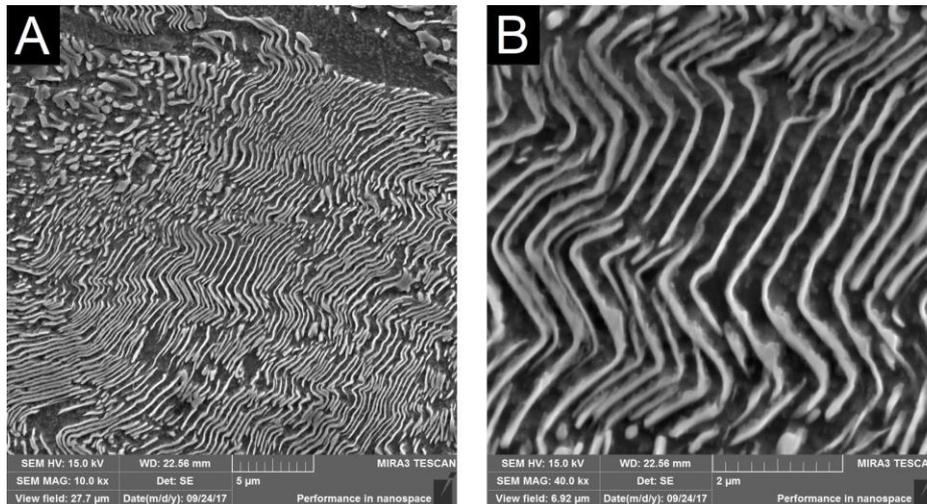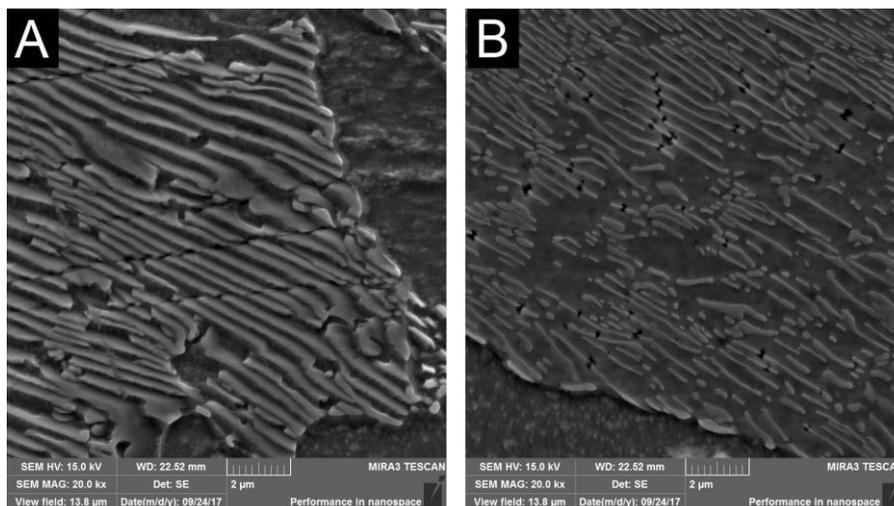

Figure 8: Pearlite colonies in CD2 sample.

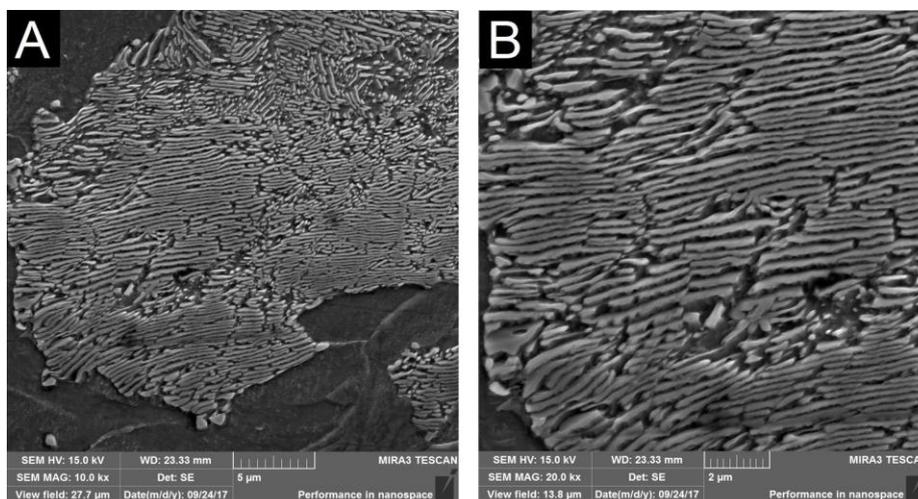Figure 9: Pearlite colonies in BD1 sample.

Figure 10: Pearlite colonies in BD2 sample.

4. CONCLUSIONS

ECAP processing of SAE 1045 steel was successfully performed in conventional and sliding bottom dies, with and without backpressure.

Punch pressure during ECAP was higher in conventional die and with the application of backpressure. The use of sliding bottom dies may ease the processing of pearlitic steels as SAE 1045.

Hardness distribution along samples was rather inhomogeneous in CD2 and SB1 samples, however, MC1 and SB2 samples presented good hardness homogeneity. Additional passes with sample rotation could improve hardness homogeneity.

SPD of ECAP led to a highly oriented microstructure, with elongated and refined grains, especially in CD2 sample.

Pearlite lamellae morphology have changed substantially after ECAP. Irregular bent lamellae, coarse lamellae with shear band and fine lamellae structures were formed.

Additional studies regarding the relation between stress state of ECAP on different die designs / backpressure and pearlite morphology are needed to explain these behaviors.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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