

# Computational Simulation of Severe Plastic Deformation:

Equal-Channel Angular Pressing (ECAP)  
processing of biomedical Ti-6Al-7Nb alloy.

---

**David Carballo-Jarquín<sup>1</sup>,**  
**Joaquín González-Hernández<sup>2</sup>,**  
**Jorge M. Cubero-Sesin<sup>3</sup>**

**Received:** August 22<sup>nd</sup>, 2017

**Accepted:** September 18<sup>th</sup>, 2017

<sup>1</sup> Simulation Engineer, Emerson Electric, San José 10201, Costa Rica. [davidcarba05@gmail.com](mailto:davidcarba05@gmail.com)

<sup>2</sup> Professor, School of Materials Science and Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica, [jegonzalez@itcr.ac.cr](mailto:jegonzalez@itcr.ac.cr)

<sup>3</sup> Professor, Ph.D., Center for Research and Extension in Materials (CIEMTEC), School of Materials Science and Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica, [jcubero@itcr.ac.cr](mailto:jcubero@itcr.ac.cr)

# ABSTRACT

Severe Plastic Deformation (SPD) techniques provide bulk materials with improved mechanical properties due to the ultrafine-grained (UFG) microstructures that can be achieved by this process. One of the most used and investigated methods of SPD is Equal-Channel Angular Pressing (ECAP). The deformation behaviour and characteristics of the material during the processing, have been researched with simulation software. The software contributes with the visual aid and the calculations of stress and strain. The information retrieved from simulations is necessary to complement experimental work and provide perspective in order to design the tools used in ECAP. This study presents a simulation of ECAP processing of commercial Ti-6Al-7Nb alloy.

# RESUMEN

Las técnicas de deformación plástica severa (SPD, por sus siglas en inglés) producen materiales volumétricos con propiedades mecánicas superiores debido a microestructuras de tamaño de grano ultrafino (UFG, por sus siglas en inglés) que pueden desarrollarse con estas técnicas. Una de las más utilizadas e investigadas en SPD es la extrusión en canal angular constante (ECAP, por sus siglas en inglés). El comportamiento y características del material durante la deformación, han sido investigadas con software de simulación. El software contribuye con la ayuda visual y cálculos de esfuerzos y deformaciones. La información recuperada de las simulaciones es necesaria para complementar el trabajo experimental y provee perspectiva para diseñar las herramientas utilizadas en ECAP. Este estudio presenta una simulación del procesamiento por ECAP de una aleación comercial de Ti-6Al-7Nb.

**Keywords:**

*severe plastic deformation, ultrafine-grained structure, equal-channel angular pressing, simulation, titanium-aluminum niobium*

**Palabras clave:**

*deformación plástica severa, estructura de grano ultrafino, extrusión en canal angular constante, simulación, titanio-aluminio niobio*

## Introduction

Severe plastic deformation (SPD) describes the effect of processing metallic alloys under a combination of extensive hydrostatic pressure and high deformations [1]. This process allows the formation of ultra-fine grains (UFG). The materials with UFG can be defined as polycrystals with an average grain size under to  $\sim 1 \mu\text{m}$ ; also, most of these materials have a highly equiaxial and homogeneous microstructures, grain boundaries with high disorientation angles; this makes it possible to achieve unique properties in the material [2]. One of these properties is the biocompatibility.

Severe plastic deformation (SPD) describes the effect of processing metallic alloys under a combination of extensive hydrostatic pressure and high deformations [1]. This process allows the formation of ultra-fine grains (UFG). The materials with UFG structures can be defined as polycrystals with an average grain size below  $\sim 1 \mu\text{m}$ . Also, most of these materials have highly equiaxed and homogeneous microstructures, grain boundaries with high misorientation angles; this makes it possible to achieve unique properties in the material [2]. One of these properties is improved biocompatibility in biomedical titanium alloys [3]. To develop tools for SPD processes such as Equal-Channel Angular Pressing (ECAP), it is necessary to collect and generate information using numerical simulation.

The biomedical alloy Ti-6Al-7Nb, processed by SPD, is expected to increase its biocompatibility properties associate to osteo-conductivity, corrosion resistance and adhesion to tissues [3]. These properties enhance the range of applications in medical industry. The application of this kind of technology has not been officially implemented in the industry, since it still is in research and development stage.

One of the most important methods of SPD is ECAP [2]. ECAP is based on two intersecting channels of equal cross-section in an oblique angle [4]. The shearing stress the sample is subjected when it goes through the corner is the main source of deformation. The transversal section of the sample

remains constant and it is possible to pass the same sample several times through the channel. Thus the process is accumulative, allowing high deformations rates [3].

In this work, simulations by FEM were done using CAE tools, to model the ECAP tooling used in the Materials Science and Engineering School of the Costa Rica Institute of Technology, specifically processing samples of Ti-6Al-7Nb through ECAP. Figure 1 presents a schematic representation of the ECAP process for the channel of  $90^\circ$  angle.

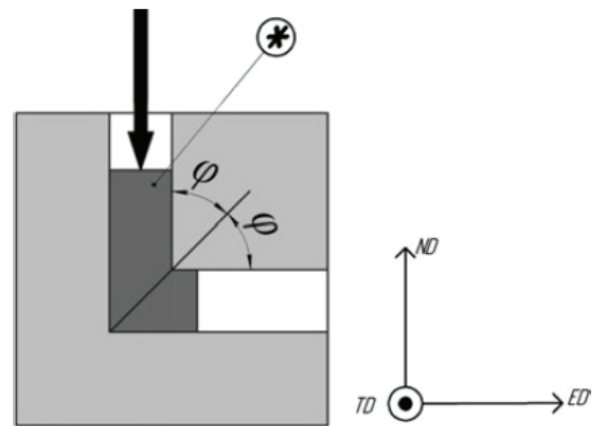


Figure 1. Schematic of equal-channel angular pressing [3].

## General Objectives

Use finite element modeling tools to analyze the stress and strain behavior of the elements (samples and tools) during equal channel angular pressing.

## Specific Objectives

- Model the geometry of the ECAP die used experimentally.
- Investigate the material properties, because the results of simulations are strongly linked to this data.
- Execute the simulations using Abaqus CAE software and analyze the results

## Justification

The general parameters and modelling conditions used are listed below as (a) and (b) respectively.

### a) General Parameters

#### i. Material Properties:

The material properties for the alloy Ti-6Al-7Nb in the simulation models are:

- Density:  $4.4 \times 10^{-9}$  ton/mm<sup>3</sup>.
- Young's Modulus: 112 GPa
- Poisson Ratio: 0.3.
- Yield Strength: 847 MPa.
- Rupture Strength: 913 MPa at 8% of elongation.

#### ii. Geometry:

The ECAP process was simulated with two configurations. Figure 2 shows the schematic for the die, this specific design counts with two channels with either a 90° or 120° angle for deformation. Figure 3 presents the assembly for the ECAP models in both possible configurations for the die, left side 90° and right side 120°.

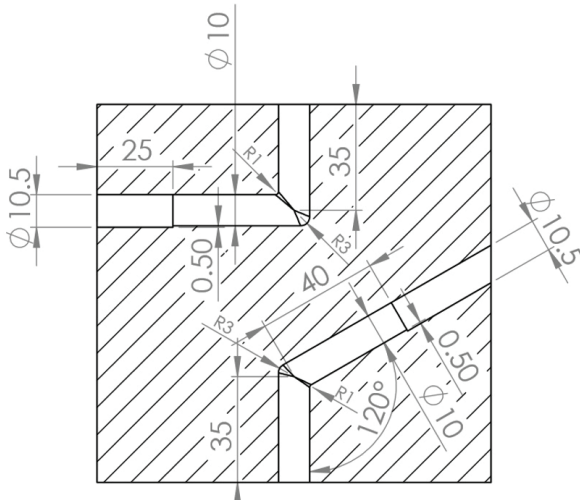


Figure 2. Dimensions for ECAP channels

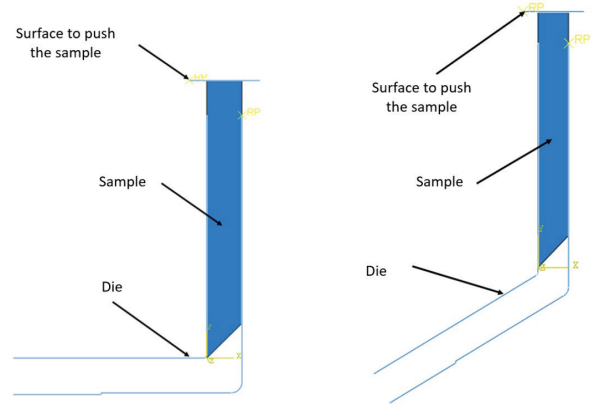


Figure 3. Assembly for ECAP simulations.

### b) Model Conditions

#### i. Assumptions

- Dies and surfaces to push the samples are rigid surfaces (they weren't taken into consideration when the model was analyzed). By using rigid surfaces, the computational cost is reduced.
- The material properties are homogeneous in the samples of Ti-6Al-7Nb. Also, the material is assumed as perfectly isotropic.
- Heat transfer due to friction is negligible.
- In ECAP the friction coefficient is 0.1 in all contact surfaces [5].

#### ii. Boundary conditions for ECAP model:

- The die will be fixed during the whole simulation, this means, it will not have any degrees of freedom available for displacement.
- The surface to push the sample will only have the vertical degree of freedom available.
- All degrees of freedom will be available for the sample.

#### iii. Equation that governs the model:

- The equation that governs the analysis for ECAP in the linear range is Hooke's Law:

Where:

: Stress.

: Young's Modulus.  
: Unitary Deformation.

- iv. Mesh used in ECAP.
  - o The mesh used in the models is made of quadrilateral elements with complete linear integration.

## State of the art

The ECAP results are shown in this section. The analysis performed provided information about the stresses in the die during the test. The contact study probes were located in the samples to check the highest stress points during the motion through the die. Figure 4 details the highest stress points by color code (blue: low, red: high).

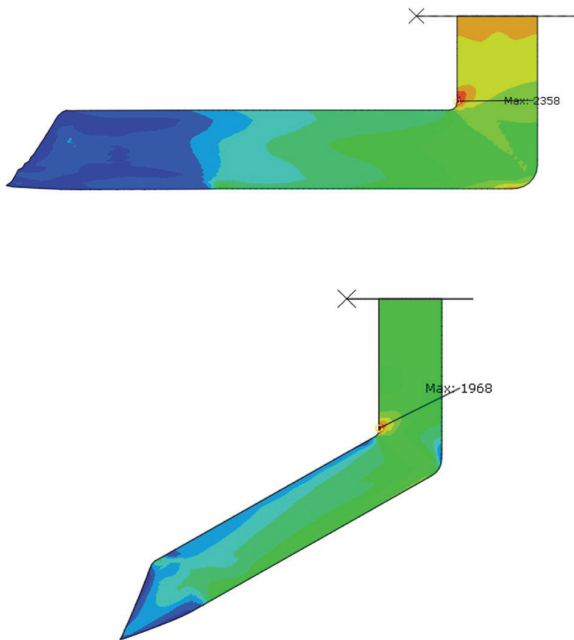


Figure 4. Probes in areas with high contact pressure (units: MPa)

Figure 5 is generated by using the contact pressure in the nodes shown in Figure 4 and the displacement of the surfaces to push the samples, which produces a graph of pressure vs displacement, meaning contact pressure and distance traveled by the probes.

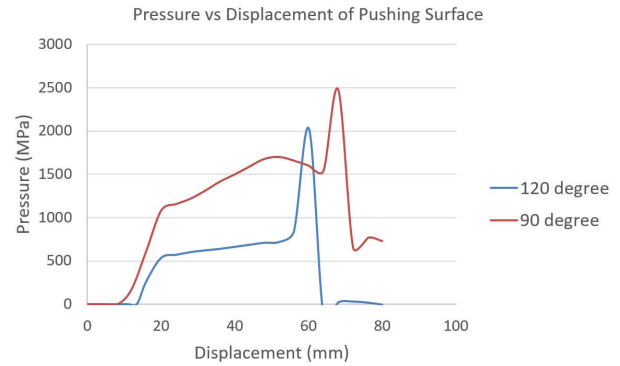


Figure 5. Contact Pressure vs Pushing Surface.

It is important to point out in Figure 5 that the die with 120° induces a decrease of around 20% in the contact pressure. In general, the shape of both curves is similar, but with an offset of 500 MPa. Regarding plastic deformation of the sample, for the 90° die, plastic deformation is higher, with zones approximately of 120% of permanent deformation. In the 120° die, areas with highest plastic deformation are only of around 60%.

Figure 6 shows plastic deformation of the sample for both 90° and 120° dies at 50% and 100% of motion through the die. Regarding material processing, this information shows higher deformation will be achieved with the 90° die.

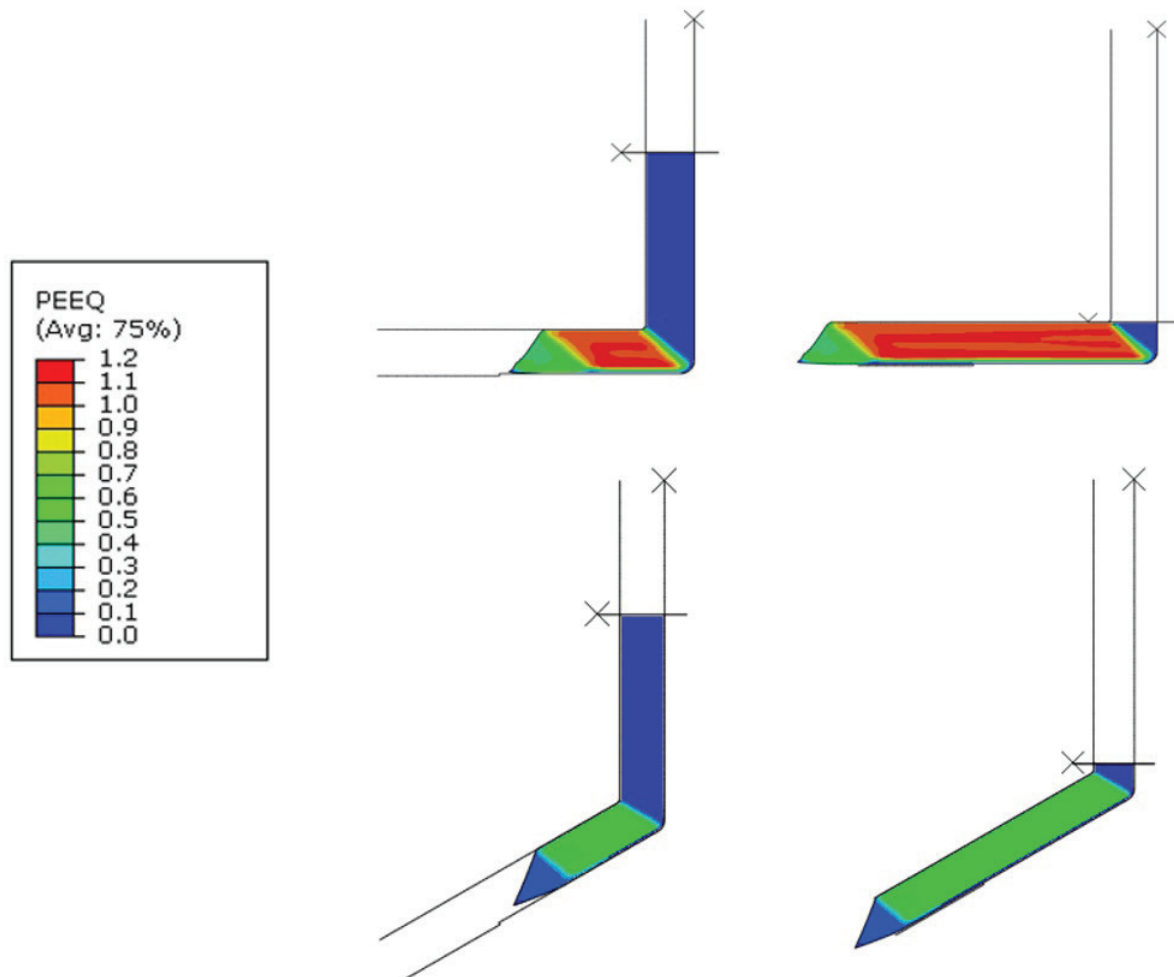


Figure 6. Plastic Deformation. Source: Author.

Finally, it is important to check the Von Mises stress in the simulation. Figure 7, shows that the process with a 90° die induces higher stresses in the sample; at 50% of travel, most of the sample has stresses above the yield strength of the alloy (847 MPa). With the 120° die, some areas are above the yield strength, however, the stresses are not as high in comparison with the 90° die.

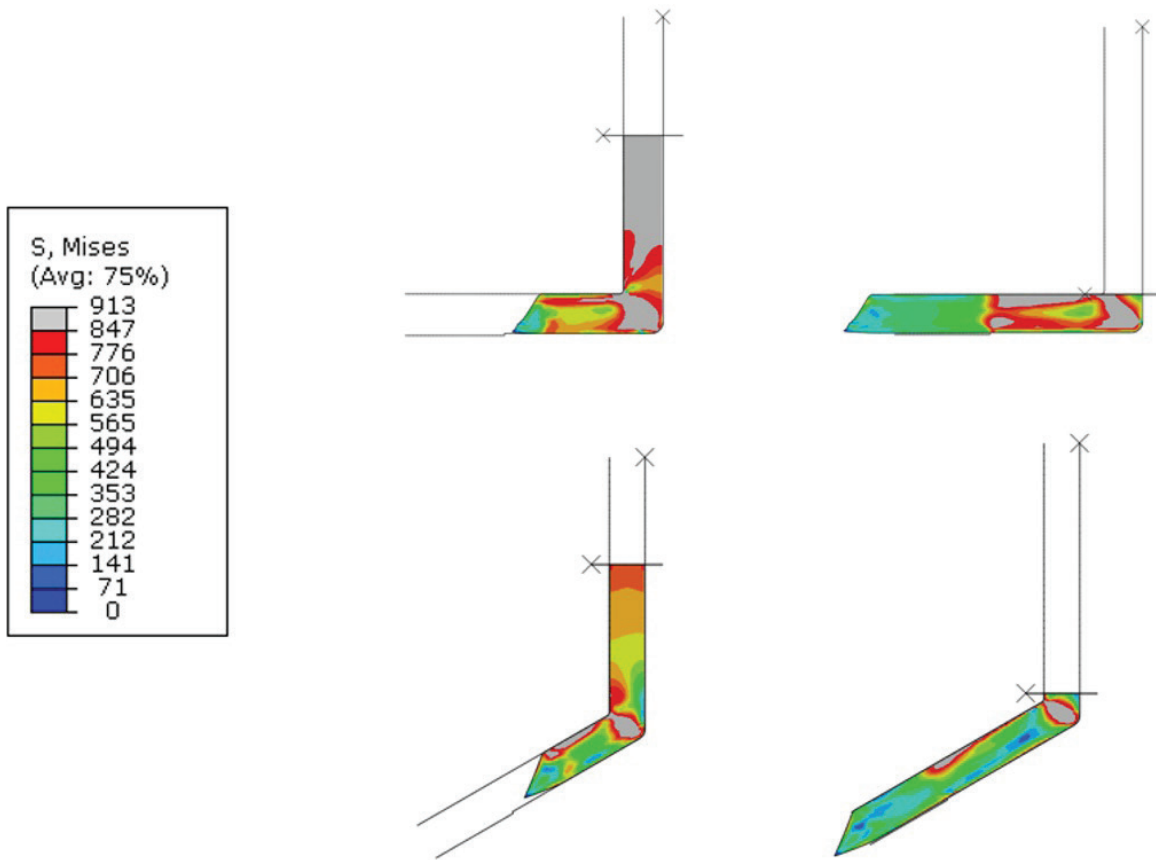


Figure 7. Von Mises Stress.

## Conclusions

- The 120° die will produce ~20% less load in comparison with the 90° die. This will produce less refinement in the crystalline structure. However, since the sample is refined by shear stress; big part of these stresses are originated from contact between the die and the sample; the greater the stresses, the greater the change in the crystalline structure.
- The change in the grain size of the material due to ECAP will be more significant for the 90° die due to the higher stress and deformation from processing.

## Acknowledgments

The authors acknowledge the support of Dr. Bruno Chinè, coordinator of the computational simulation lab of the Center for Research and Extension in Materials, School of Materials Science and Engineering, Costa Rica Institute of Technology. DC thanks the professors of the Master Degree Program of Medical Device Engineering of the Costa Rica Institute of Technology for support and advice.

## References

- [1] Khoddam, S., Hodgson, P., Zarei-Hanzaki, A. and Yan Foon, L. (2016) A simple model for material's strengthening under high pressure torsion, *Materials and Design*, 99, 335-340.

- [2] Valiev, R.Z., Estrin, Y., Horita, Z., Langdon, T., Zehetbauer, M.J. and Zhu, Y.T. (2006) Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation, *JOM*, 58(4), 33-39.
- [3] Estrin, Y. and Vinogradov, A. (2013) Extreme grain refinement by severe plastic deformation: A wealth of challenging science, *Acta Materialia*, 61(3), 782-817.
- [4] Kim, H.S. (2002) Evaluation of strain rate during equal-channel angular pressing, *Journal of Materials Research*, 17(1), 172-179.
- [5] Yoon, S.C., Bok, C.H., Seo, M.H., Kim, T.S., Kim, H.S. (2008) Comparison in Deformation and Fracture Behavior of Magnesium during Equal Channel Angular Pressing by Experimental and Numerical Methods, *Materials Transactions*, 49(5), 963-966.
- [6] ASTM International (2016) Standard Specification for Wrought Titanium-6Aluminum-7Niobium Alloy for Surgical Implant Applications (UNS R56700), ASTM-F1295-16.
- [7] Niinomi, M. (1998) Mechanical properties of biomedical titanium alloys, *Materials Science & Engineering A*, 243(1-2), 231-236.
- [8] Conejo-Herrera, M. (2016) Simulación del procesamiento de una aleación de Ti-6Al-7Nb por Equal-Channel Angular Pressing (ECAP) mediante el método de elementos finitos, *Lic. thesis*, Instituto Tecnológico de Costa Rica.
- [9] Görtan, M. O. (2014) Severe plastic deformation of metallic materials by equal channel angular swaging: Theory, experiment and numerical simulation, Ph.D. thesis, Technische Universität, Darmstadt.

## Bibliography

- x S. Khoddam, P. Hodgson, A. Zarei-Hanzaki and L. Yan Foon, "A simple model for material's strengthening under high pressure torsion," p. 6, 2016.
- [2] R. Valiev, Y. Estrin, Z. Horita, T. Langdon, M. Zehetbauer and Y. Zhu, "Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation," p. 7, 2006.
- [3] Y. Estrin and A. Vinogradov, "Extreme grain refinement by severe plastic deformation: A wealth of challenging science," p. 36, 2013.
- [4] H. Kim, "Evaluation of strain rate during equal-channel angular pressing," *Department of Metallurgical Engineering, Chungnam National University, Korea*, p. 8, 2001.
- [5] C. H. B. M. H. S. T.-S. K. H. S. K. Seung Chae Yoon, "Comparison in Deformation and Fracture Behavior of Magnesium during Equal Channel Angular Pressing by Experimental and Numerical Methods," *Materials Transactions*, vol. 49, pp. 963-966, 2008.
- [6] A. International, Standard Specification for Wrought Titanium-6Aluminum-7Niobium Alloy for Surgical Implant Applications (UNS R56700), 2016.
- [7] M. Niinomi, "Mechanical properties of biomedical titanium alloys," *Materials Science & Engineering*, pp. 231-236, 1998.
- [8] M. C. Herrera, *Simulación del procesamiento de una aleación de TI-6AL-7NB por Equal-Channel Angular Pressing (ECAP) mediante el método de elementos finitos*, San José: Instituto Tecnológico de Costa Rica, 2016.
- [9] M. O. Görtan, *Severe plastic deformation of metallic materials by equal channel angular swaging: Theory, experiment and numerical simulation*, Darmstadt: Technischen Universität Darmstadt, 2014.