# INFLUENCE OF DEFORMATION TECHNOLOGY ON FATIGUE PROPERTIES OF TITANIUM

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***Resume***

The influence of commercially pure Titanium microstructure on fatigue properties and their improvement or deterioration is analyzed in the presented contribution. One tested material was after cold drawing the other after severe plastic deformation by Equal Channel Angular Pressing (ECAP). Intense plastic deformation (ECAP) resulted in yield point 100 % higher and UTS 97 % higher than obtained by traditional cold drawing. The ductility was 57 % lower than for cold drawing. However, the fatigue properties namely the degradation of fatigue properties were influenced by sever plastic deformation in a way not consistent with the usually counted influence on mechanical properties and more, the fatigue limit was lower for high numbers of loading cycles. For $N = 5.5 \times 10^5$ the fatigue limits in torsion $\tau_C$ for Ti after ECAP and after cold drawing were identical. For $N < 5.5 \times 10^5$ cycles the $\tau_C$ for Ti after ECAP was higher, but for $N > 5.5 \times 10^5$ cycles it was lower.

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## 1. Introduction

Materials engineering is aimed first at useful properties improvement for both traditional, and newly developed advanced materials. The cold drawing is supposed to be a traditional technology. The way the mechanical properties of materials are improved by plastic deformation depends on the technology applied (surface treatment, deep deformation in volume, stress field distribution etc.) and on the nature of the material in question. Any plastic deformation is accompanied by internal residual stress field, which is later able to influence the fatigue damage and fatigue crack growth [1, 2]. Surface strengthening by plastic deformation builds up compression stress in surface layers, which improving fatigue properties. By the same kind of deformation contrariwise in layers under the surface tension stress builds up, which can have detrimental influence on fatigue properties, and can cause marked degradation at high fatigue cycle numbers [3, 4].

The microstructure of the material is influenced by cold working significantly. The polyhedral microstructure is replaced by a non polyhedral (so called deformation texture). After severe plastic deformation untraditional, extremely fine microstructures can be obtained. Severe plastic deformation by simple shear strain [5, 6] or by angular pressing, with constant cross section and by repetition of the pressing can produce a very fine microstructure (grain size < 10 μm, or < 100 μm) [7]. The microstructure obtained this way in metallic materials (pure metals and alloys based on Fe, Cu, Al, Ni, Ti) shows unique mechanical and physical properties [8, 9]. However, for safety reasons it is important to learn the intensity of mechanical properties degradation, appearing first at variable stress loads e.g. fatigue.

The aim of this contribution is to analyze and compare the fatigue properties of specimens made of commercially pure Titanium by cold drawing and by severe plastic deformation (ECAP). We consider it important for the application of these materials in safe service.

## 2. Experimental method

Commercially pure Ti was tested on rods with diameter d = 10 mm. The rods were purified by zonal refinement and cold drawn (cross section reduction about 20 %). The other rods with diameter $d_0$ = 7.56 mm were made by the technology of Equal Channel Angular Pressing (ECAP, 4 passes at temperature of 460 °C). Microstructures were analyzed on polished specimens and thin foils by optical and electron microscopy. Mechanical properties were obtained by standard static tensile tests and HV10 hardness testing. Fatigue properties were evaluated by fatigue tests in torsion (R = -1) using test rods $d_0$ = 6 mm in diameter.

Test results were analyzed to define the influence of the manufacturing technology on the fatigue characteristics, tested properties of the material, first of all with the aim to define safe functionality in service.

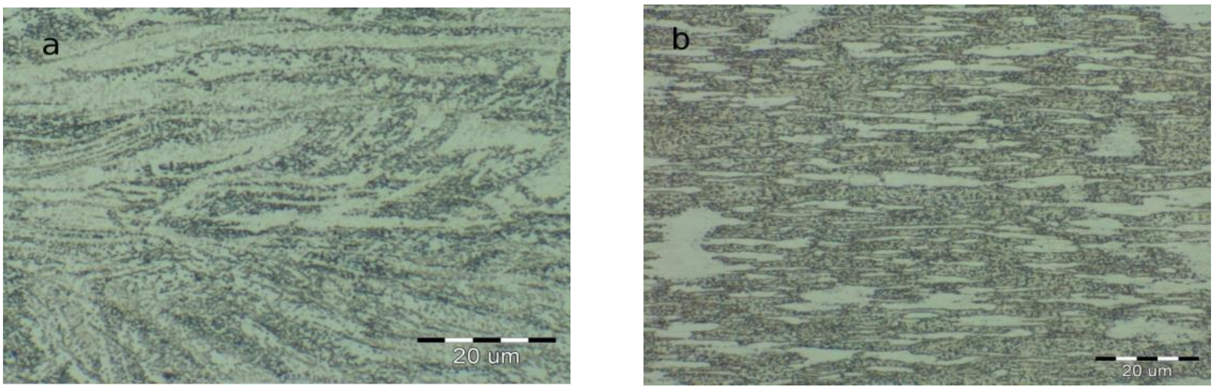
## 3. Experimental results and discussion

The microstructures of the tested materials after cold drawing and ECAP were non polyhedral with strong deformation texture. The microstructures of specimens after ECAP were finer and more uniform (Fig. 1).

Microstructure in the cross section of the rods showed, that the Widmannstätten microstructure formed by the zonal refinement remained after cold drawing (Fig. 2a). The ECAP microstructure was granular (Fig. 2b).

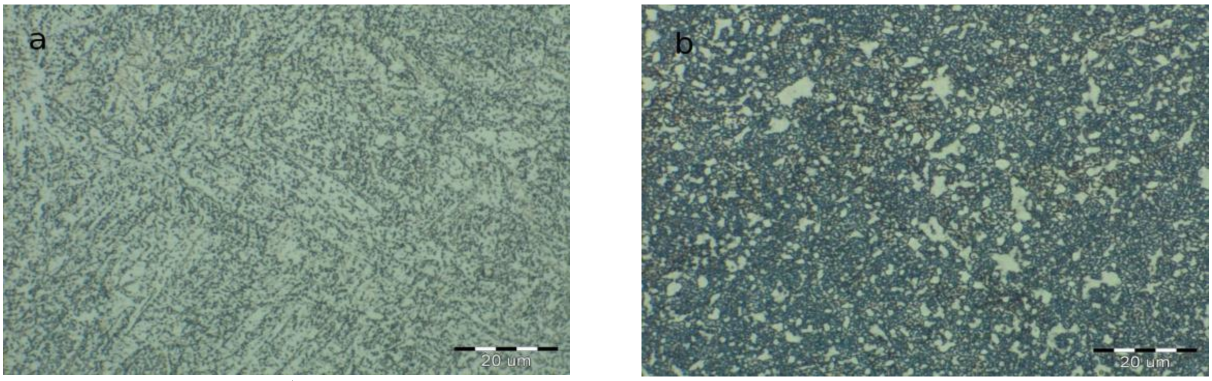
Both shown microstructures were different from those in Ti in equilibrium condition, which is typically polyhedral. Differences are in grain size, grain form, dislocations density, and in the presence of sub grains. It has important results: the outstanding improvement of strength properties and the decrease of plastic properties. Generally, the fatigue properties are strength dependent but predict fatigue properties by the microstructure is much more complex than doing it for the mechanical properties.

The mechanical properties tested by tensile testing and hardness HV tests are in Tab. 1.




*a)* *b)*

*Fig. 1. Microstructure of samples in longitudinal direction: a) cold drawn, b) ECAP.*




*a) b)*

*Fig. 2. Microstructure in transverse direction: a) cold drawn, b) ECAP.*

*Table 1*

*Mechanical properties of tested Ti samples.*

| Deformation technology | $R_{P0.2}$[MPa] | $R_m$ [MPa] | $A_5$ [%] | Z [%] | HV10 |
|---|---|---|---|---|---|
| **Cold Drawing** | 645 | 665 | 17 | 66.5 | 203 - 214 |
| **ECAP** | 1290 | 1310 | 10 | 51 | 321 - 333 |

*Table 2*

*Fatigue properties of tested samples.*

| Technology | $R_m$ [MPa] | $\tau_C 10^5$ [MPa] | $\tau_C 10^6$ [MPa] | $\tau_C 10^7$ [MPa] | $\tau_{C/N}/R_m$ $10^5$ | $10^6$ | $10^7$ |
|---|---|---|---|---|---|---|---|
| **Drawn** | 665 | ± 231 | ± 172 | ± 151 | 0.35 | 0.26 | 0.23 |
| **ECAP** | 1310 | ± 256 | ±160 | ±120 | 0.20 | 0.12 | 0.09 |

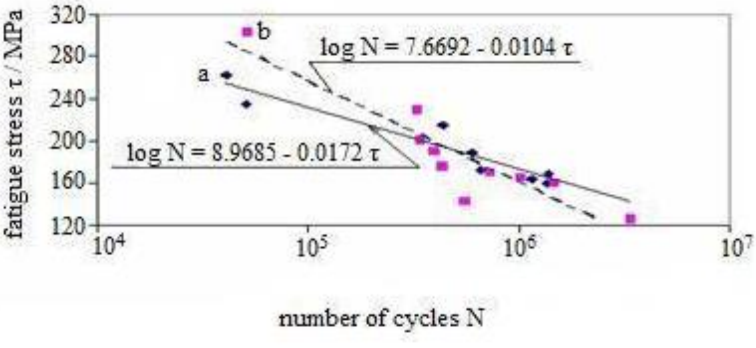



*Fig. 3. Wohler´s curve for torsion tests: a) cold drawn, b) ECAP.*
*(fullcolour version available online)*

Comparison of mechanical properties in Tab. 1 showed that the specimens made by ECAP showed an increase of the yield point RP0,2 for about 100 %, UTS $R_m$ for about 97 % and hardness HV10 about 57 % than the cold drawn specimens, but the ductility decreased for about 59 %. The fatigue test results are shown in the plot: fatigue stress level on number of cycles to fracture in Fig. 3. The calculated fatigue characteristics are in Tab. 2

As can be seen in references [10, 11] the relation between the strength and fatigue limit is usually described by a parametric formula: $\sigma_C = k.\ R_m$, where the parameter k depends on the nature of the material. Generally it can be considered that higher the ultimate tensile strength $R_m$, the lower the ratio $\sigma_C/R_m$. This behaviour was also confirmed by the experiments in this work for both production technologies of Ti. For higher number of loading cycles, as supposed, the ratio $\tau_C/R_m$ is decreasing. The decrease is more significant for ECAP technology, for which the strength $R_m$ is 97 % higher than for cold drawn specimens (See Fig. 4.).

The absolute values of $\tau_{CN}$ were identical at cycle number N = 5.64 x $10^5$ ($\tau_C$ 5.64 x $10^5$ = ± 194 MPa). For cycle number of N > 5.64 x $10^5$ was the fatigue limit $\tau_{CN}$ for the cold drawn material higher than that for he test rods after ECAP. As results show, the strength increase by plastic deformation is not an unlimited method for the increasing of fatigue properties, and contrariwise it can end up with a decrease.

Plastic deformation is accompanied by internal residual stress fields, changes in the microstructure morphology, damage accumulation, growth of accumulated energy in the material etc. The behaviour of deformation strengthened materials in the process of fatigue is influenced by these facts mentioned in references [3, 4, 11]. The influence of cold work on fatigue this way is ambiguous. Beneficial is clearly the influence of compressive residual stress fields, and the grain refinement (sub grain formation) by strain. Adverse is the influence of defects accumulation, short micro cracks in the structure, inclusions (first by their cracking and breaking), and the accumulation of defects on grain boundaries. Also adverse can be the effect of areas with tensile residual stress fields and the exhausted plasticity caused by previous deformation. These factors, especially with the increasing number of cycles can accelerate the degradation process of fatigue. Intensive plastic deformation significantly reduces plasticity and therefore some short cracks can attain a critical length and further spreads as fatigue cracking.

The fatigue test results in torsion showed, that the production technology by plastic deformation and the obtained residual stress and the microstructure influenced markedly the fatigue limit in torsion and the number of cycles to fracture as can be seen in Figs. 3 and 4. Though the UTS obtained by the ECAP technology was very high, the other adverse factors accompanying the technology caused degraded fatigue properties in torsion for high cycle numbers. Fractography of the tested broken specimens confirmed that fatigue process did not take place in the direction of maximum shear stress. In Fig. 5 are the broken torsion fatigue test pieces.

The cracks in both samples were initiated in the direction of the specimens' axis, and the crack growth has changed the direction into the planes controlled by shear stress, after the crack reached the critical length. During torsion the maximum shear stress is in the angle 45° to the longitudinal axis and the crack is supposed to grow in this direction, as it was for the test specimen made of a Ti6 Al4 alloy (See Fig. 5c). The fracture surfaces of both compared materials after fatigue testing show clear fatigue damages (Fig. 6). The fracture surfaces for cold drawn specimens are more rugged.

According to the experimental results the fatigue crack initiation and growth at stress levels $\tau < \tau_{max}$ in longitudinal direction was assisted by micro crack nuclei generated by plastic deformation. This caused lower fatigue properties in symmetrical torsion, and it can make the high strength properties of this material unusable. For fatigue in tension – compression the properties could be considerably better. As shown, for long life at repeated loads in torsion, the tested deformation strengthened Ti, cannot be profitable, though the point of strength properties can offer significant weight reduction, important in applications in many fields [8, 9]. Titanium alloys are preferred due their high strength properties, as it was in the tested materials and they retain the other excellent properties of pure Ti (resistance to corrosion, low weight loss by friction, biocompatibility etc.).

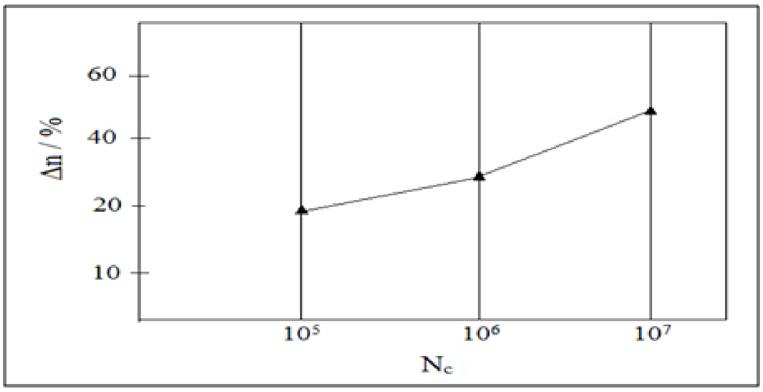
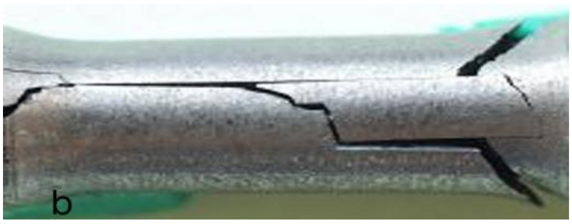
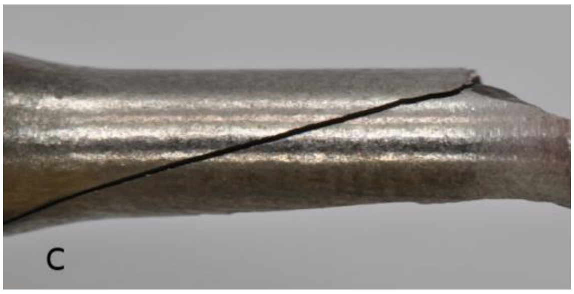



*Fig. 4. Comparable decrease of $\sigma_{CN}/R_m$ by ECAP compared to cold drawing. Dependence of Δn on the number of cycles N.*


a)




b)




c)

*Fig. 5. Broken test specimens after fatigue tests in torsion: a) cold drawn, b) ECAP, c) alloy Ti6 Al4 V.*

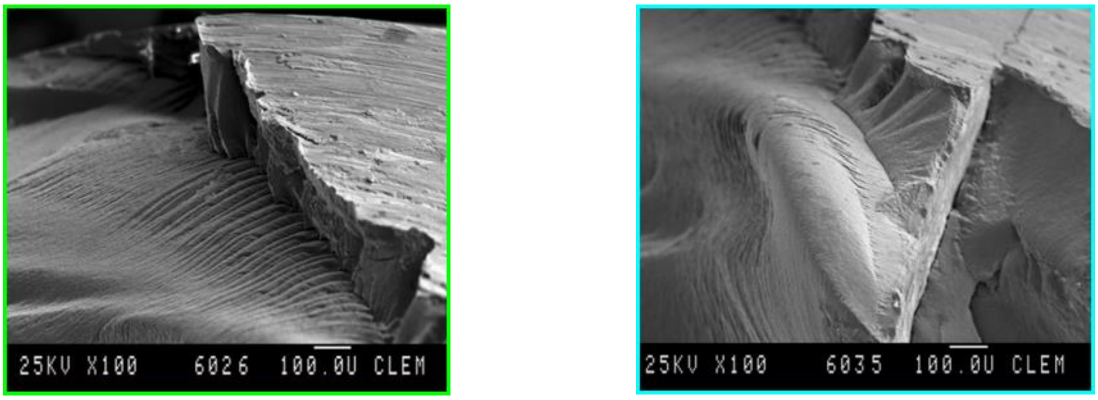



*Fig. 6. Fracture surface morphology – ECAP*

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## 4. Conclusions

The influence of deformation technology on basic strength and torsion fatigue properties of commercially pure Titanium was analyzed in this contribution. The specimens for tensile tests and torsion fatigue (R = -1) tests were made of cold drawn rods and rods produced by angled pressing (ECAP – 4x at temperature of 460 °C).

1. Microstructure of the cold drawn specimens was non polyhedral, with grains elongated in the drawing direction retaining the so called Widmanstätten morphology. By ECAP a super fine grained microstructure was produced, the grains were aligned in rows in the rod axis direction. Both applied technologies increased the strength properties significantly. Ultimate tensile strength and hardness increased, but the ductility decreased. The rods after ECAP showed yield point 100 % higher and UTS 97 % higher, than obtained by cold drawing. The ductility was 57 % lower, than for cold drawing.

2. By the ECAP technology it is possible to produce high strength properties for pure Ti ($R_m$ = 1310 MPa), and satisfactory ductility ($A_5$ = 10%).

3. For cyclic loading in torsion after both applied technologies, the fatigue limit decreased significantly for higher numbers of cycles. The specimens after ECAP showed a higher degree of fatigue properties degradation.

At the number of cycles $10^5$ for ECAP the value $\tau_C$ was about 11 % higher, but at $10^7$ the $\tau_C$ was about 20 % lower than it was for cold drawn specimens.

The fatigue limit values for symmetric torsion are low ($\tau_C$ $10^7$= 151 MPa for cold drawing and $\tau_C$ $10^7$= 120 MPa for ECAP) due to crack propagation in the direction of rod axis (avoiding the maximum stress direction). It is supposed it was due the small defects and cracks produced by deformation strengthening.

### References

[1] J. Hidvéghy, J. Micheľ, M. Buršák: Mater. Eng. 9(3) (2002) 116-124.

[2] J. Hidvéghy, J. Micheľ, M. Buršák: Metalurgija 42(2) (2003) 103-106.

[3] K. Kovaľová, I. Mamuzič, M. Buršák: Metalurgija 43(4) (2004) 335-338.

[4] M. Buršák, O. Bokůvka: Communications (4) (2006) 34-37.

[5] V.M. Segal, V.I. Reznikov, A.E. Drobyshevskiy, V.I. Kopylov: Rus. Metal. 1 (1981) 99-105.

[6] T. Kvačkaj, R. Kočiško, J. Bidulská, R. Bidulský, J. Dutkiewicz: Chem. Lett. 105 (2011) 514-516.

[7] R.Z. Valiev, N.A. Krasilnikov, N.K. Tsenev: Mater. Sci. Eng. A 137 (1991) 35-40

[8] J. Petruželka, I. Dluhoš, D. Hrušák, J. Sochová: Czech. Stomat. 106(3) (2006) 72-77.

[9] I. Bernáthová, M. Buršák: Metalurgija. 50(4) (2011) 249-252.

[10] F. Trebuňa, M. Buršák: Limit values - fractures, Grafotlač Edition, Prešov, 2002.

[11] A. Puškár: High frequency fatigue of materials, Edition Center of Žilina University, Žilina 1997.

[12] S. Konvičková, J. Valenta: Biomechanics of Human knucklebones and their replacements, Vienala Edition, 2000.