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Mechanical and Microstructural Properties of Rotary-Swaged Wire of Commercial-Purity Titanium

Michal Duchek, Jan Palán, Tomas Kubina

Abstract**—**Bars made of titanium grade 2 and grade 4 were subjected to rotary forging with up to 2.2 true strain reduction in the cross-section from 10 to 3.81 mm. During progressive deformation, grain refinement in the transverse direction took place. In the longitudinal direction, ultrafine microstructure has not developed. It has been demonstrated that titanium grade 2 strengthens more than grade 4. The ultimate tensile strength increased from 650 MPa to 1040 MPa in titanium grade 4. Hardness profiles on the cross section in both materials show an increase in the centre of the wire.

Keywords**—**Commercial-purity titanium, wire, rotary swaging, tensile test, hardness, modulus of elasticity, microstructure.

I. Introduction

WHEN we focus on strength of materials, which is one of their key properties from the user's standpoint, we can identify several ways to increase it. There are several fundamental mechanisms for improving strength, i.e. types of strengthening. One of them is strain hardening. Another method involves alloying, where the solid solution is strengthened by substitutional or interstitial elements. Further options include grain size strengthening, precipitation strengthening and dispersion strengthening.

In the case of commercial-purity titanium, all the above-named mechanisms are available. For instance, the requirement for improved strength is decisive when some of the materials used in dental implants are to be replaced with titanium [1]. A designer of components of pure titanium can choose from four titanium chemistries specified by standards, which are identified by numbers from 1 to 4. With the increasing number, the content of impurities rises, both substitutional and, more importantly, interstitial elements. The levels of the following elements are those of the greatest interest: iron, carbon, and several gases: oxygen, hydrogen and nitrogen. These elements have the strongest impact on the solid-solution strengthening of the α-phase in titanium. The α-phase has a hexagonal close-packed crystal structure. It does not offer many slip systems for plastic deformation. It has one slip plane, which is the basal plan (0001), with the slip directions [2110]. Hence, there are three slip systems in total [2]. Furthermore, this structure is expected, particularly at small strains, to undergo deformation primarily by twinning a mechanism which is based on partial dislocation glide.

Rotary swaging is a forging process that is used for reducing the cross sectional area of tubes, bars and wires [3]-[6]. It is mainly employed for mechanical working of round sections. That being said, workpieces with other symmetric cross-sections can be processed as well, such as square and octahedral sections. The advantages of the process include short cycle times, good final surface quality and tight dimensional tolerances. An example of the configuration of swaging dies is shown in Fig. 1. The dies are mounted in a moving head with rollers. As the swaging dies move past and make contact with the rollers, they extend inward, toward the axis of symmetry, and reduce the cross-sectional area of the workpiece. The material is fed gradually through the swaging dies. The overall reduction is determined by the cross-section of the swaging die and that of the starting blank. In the process, local deformation in a small part of the workpiece takes place repeatedly at a high frequency. Thanks to the very favorable stress state in the workpiece induced during deformation, the process can be used for further processing of materials worked by SPD processes (SPD – severe plastic deformation).

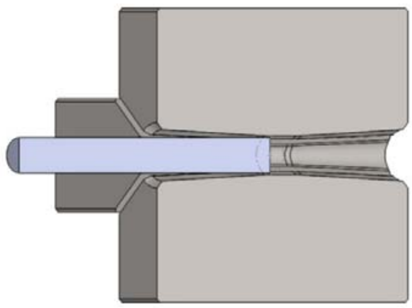

Fig. 1 Cross-sectional view of the working part of the rotary swager

II. Experiments

The experimental materials were in the form of 10 mm-diameter bars of commercial-purity titanium grade 2 and grade 4. The stock had not been heat-treated in any way prior to the forming experiments. Chemical compositions are given in Table I. Wire specimens were produced by progressive working in a rotary swager using 8 sets of swaging dies. The final wire diameters were: 8.13, 7.18, 6.48, 5.87, 5.22, 4.73, 4.25 and 3.81 mm. The resulting total logarithmic elongation e was 2.2. True strain was calculated from:

M. Duchek is head of the Metallurgical Technologies Department, Comtes FHT a.s., Průmyslová 995, 334 41 Dobřany, Czech Republic (corresponding author, phone: +420 377 197 330 or +420 607 703 315; e-mail: michal.duchek@comtesfht.cz).

J. Palán is with the Metallurgical Technologies Department, Comtes FHT a.s., Průmyslová 995, 334 41 Dobřany, Czech Republic (e-mail: jpalan@comtesfht.cz).

$$e = \ln \frac{d_0^2}{d_n^2} \quad (1)$$

where d_0 and d_n are the starting bar stock and final wire diameters. Expressing deformation in this form was advantageous, as it corresponded to the shape of the wire and the strain intensity.

The speed of the head with the rollers was approximately 350 rev·min^{-1}. The wire feeding rate was approx. 3 m·min^{-1}. Specimens for tensile testing and metallographic examination were taken from each forged wire.

Longitudinal and transverse metallographic sections were prepared by mechanical grinding and polishing. In the final polishing step, 10% hydrogen peroxide solution with colloidal silica of 50 nm mean grain size was used. The microstructure was revealed by etching with Kroll's reagent. Micrographs were taken using Nikon Eclipse MA 200 optical microscope.

Durascan 50 automatic hardness tester was used for measuring microhardness. Hardness represented by the HV1 Vickers hardness number was measured on longitudinal sections through the specimens. HV0.3 load was used for transverse sections.

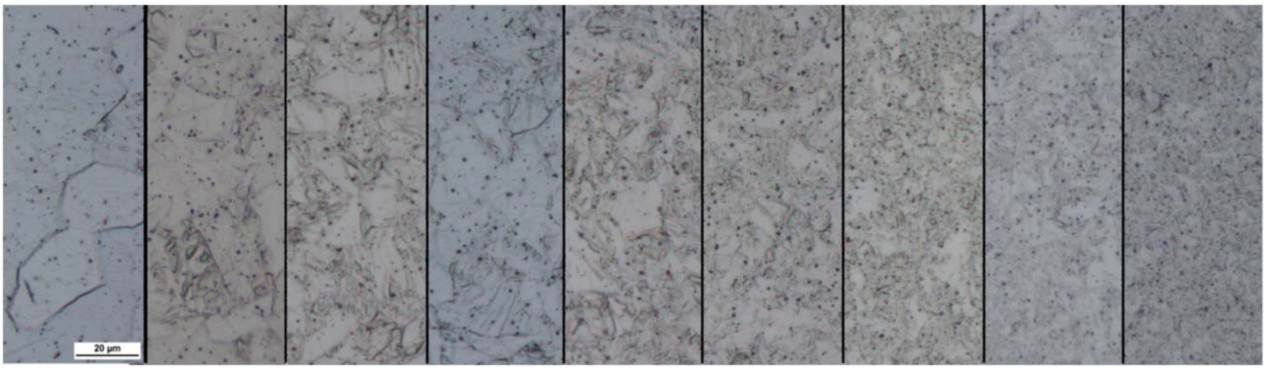

Fig. 2 Evolution of the microstructure of titanium grade 2 wire shown at the centre of its transverse section; wire diameters from left: 8.13, 7.18, 6.48, 5.87, 5.22, 4.73, 4.25 and 3.81 mm

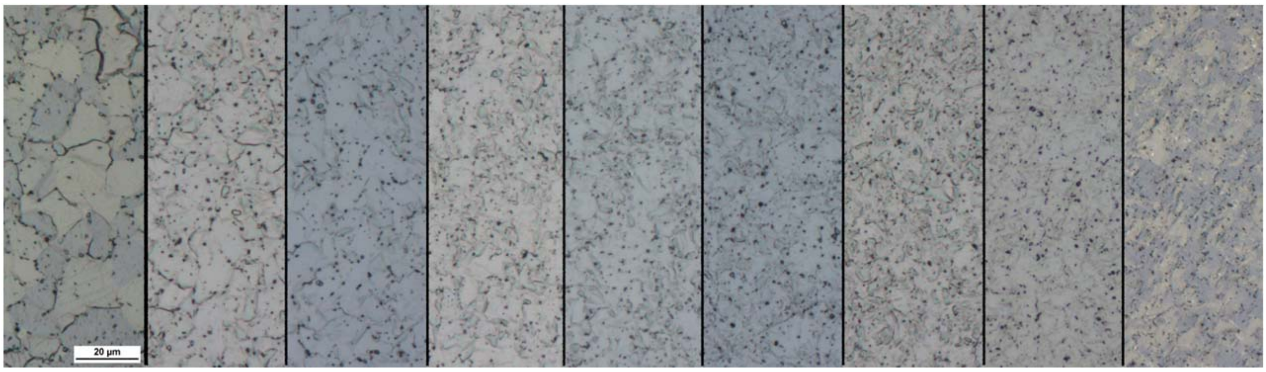

Fig. 3 Evolution of the microstructure of titanium grade 4 wire shown at the centre of its transverse section; wire diameters from left: 8.13, 7.18, 6.48, 5.87, 5.22, 4.73, 4.25 and 3.81 mm

Nanohardness was measured using the Micro Materials Nano Test Vantage nanoindentation tester. Berkovich indenter and a load of 50 mN were employed. Nanoindentation was carried out on polished longitudinal sections. Ten impressions were made at each distance from the specimen surface. The mean Young's modulus E was calculated.

Tensile testing was carried out using electromechanical testing machines and mechanical extensometers.

TABLE I
CHEMICAL COMPOSITION OF TITANIUM BARS

	Fe	O	C	H	N
CP-Ti gr.2	0.46	0.12	0.023	0.0026	0.0076
CP-Ti gr.4	0.5	0.4	0.1	0.0125	0.05

III. MICROSTRUCTURAL CONDITION

Microstructure was examined on longitudinal and transverse sections. The starting grain size in Ti grade 2 was approx. 45 µm; in Ti grade 4 it was approx. 18 µm. On the longitudinal cross-section, the grains in both materials became elongated in the longitudinal direction while their width in the transverse direction decreased due to cold deformation. No signs of recovery were found. Micrographs of the transverse sections in individual wires are shown in Figs. 2 and 3. The mean grain size became much finer, near an estimated 1 µm in both titanium materials. However, ultrafine microstructures of the kind produced by SPD processes as described by some authors [7] cannot be considered here. Texture would have to be examined using X-ray methods [8].

IV. Mechanical Properties

Tensile test data were plotted against the total accumulated true strain. The plot of ultimate strength Rm and offset yield strength Rp0.2 is shown in Fig. 4. The values for the starting bars of 10 mm diameter are plotted at the total strain of 0. The differences in strength are due to interstitial elements. Their level is higher in titanium grade 4, including the one with the most profound effect: oxygen.

The ratio of the starting strengths for both materials is 1.36. At the total strain of 2, the ratio of their ultimate strengths is 1.22. With increasing strain, both materials undergo work hardening. More appreciable strengthening can be seen in titanium grade 2 where it appears that lower content of interstitial elements allows dislocations to accumulate more extensively in the solid solution. On the other hand, better values are found in titanium grade 4 where initial strengthening due to interstitial elements takes effect. As a result, reduction to the diameter of 3.81 mm led to an ultimate strength of 1040 MPa, while the starting value was 650 MPa. The curve of the offset yield strength Rp0.2 matches relatively well the curve of ultimate strength. The value of A5 elongation decreases steeply after the first two reductions. Afterwards, it remains below 10% in titanium grade 4, as illustrated in Fig. 5. Titanium grade 2 shows better elongation values: between 10 and 15%.

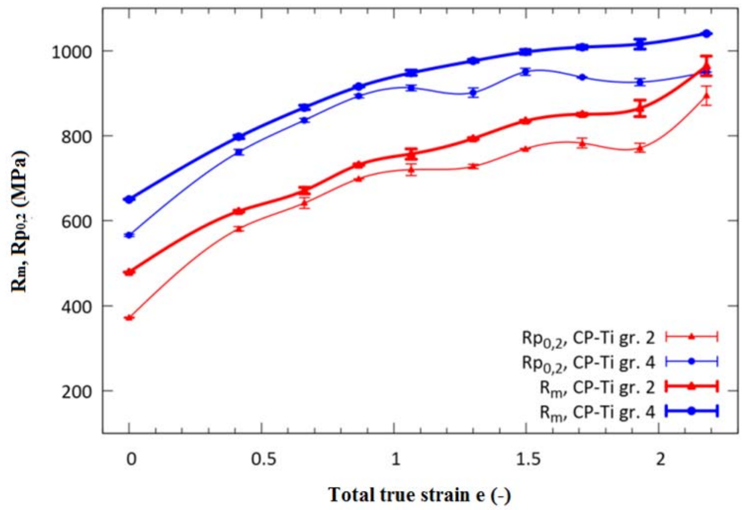

Fig. 4 Ultimate strength Rm and offset yield strength vs. total true strain e in titanium grades 2 and 4

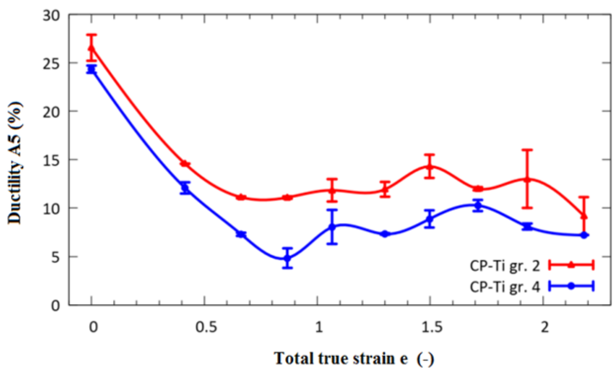

Fig. 5 Elongation A5 vs. total true strain e in titanium grades 2 and 4

Hardness profiles HV1 and HV0.3 on longitudinal and transverse sections, respectively, through rotary-swaged wires were measured. At each distance from the wire axis, hardness was more or less constant along the length of the wire. A more interesting picture emerges after examining the transverse section. Fig. 6 shows hardness profiles between the surfaces and centres of specimens of titanium grade 2 plotted with respect to the relative distance (0 representing the edge and 1 representing the centre). Despite fluctuation, a trend can be seen where the surface hardness is, on average, 10 HV0.3 less than the hardness value at the centre. This is in agreement with the conclusions derived in [9] for rotary-swaged copper wires. In drawn products, the hardness profile is opposite, with the highest values near the wire surface. This fact can be useful in processing wires produced by a continuous SPD method [10], [11] in which surface microcracks may be present. In such case, further reduction of cross-sectional area can be better achieved by rotary swaging which causes less hardening in the surface.

For comparison, a profile of the modulus of elasticity was measured using a nanoindentation tester. The plots are shown in Fig. 7. In the starting condition, the modulus of elasticity fluctuates between the surface and the centre of the bar (from the surface down to approximately mid-radius). After reductions to 8.13 and 7.18 mm, the values of the modulus of elasticity across the cross section become more equal, with the exception of a surface layer with a thickness of approximately 0.1 of the wire diameter, in which modulus of elasticity is much lower. After reduction to 6.43 mm, this deviation disappears.

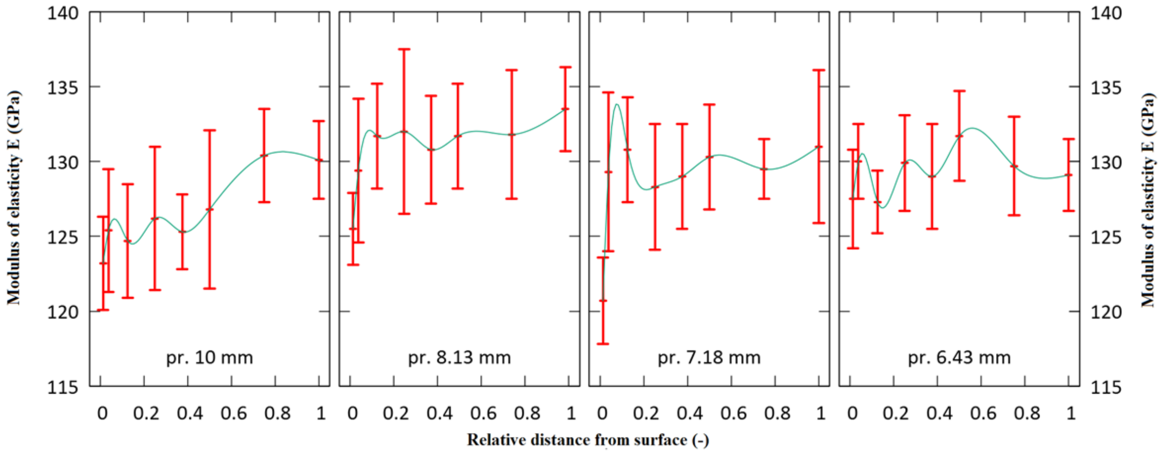

Fig. 6 Depth profile of hardness on the transverse section through titanium grade 2 wire plotted against the relative distance from the surface

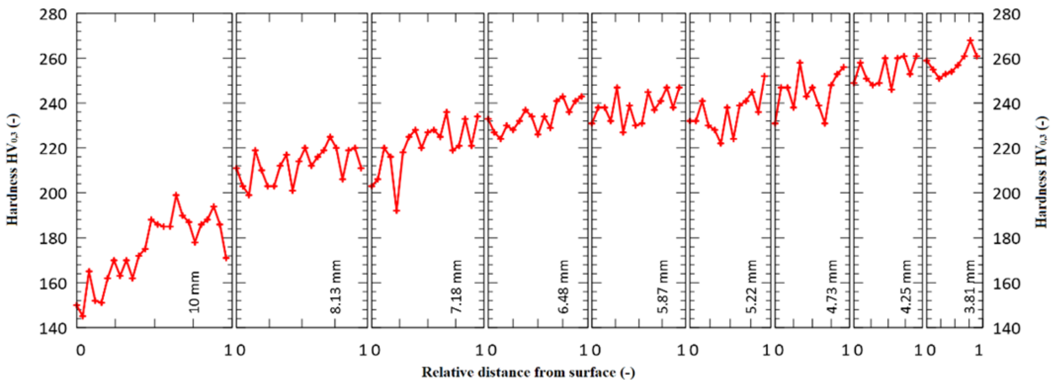

Fig. 7 Depth profile of the modulus of elasticity on the transverse section through titanium grade 2 wire plotted against the relative distance from the surface

The value of the modulus of elasticity depends on the amount of lattice defects [13]. Whereas the recrystallized material exhibits the specification-sheet value of the modulus of elasticity, accumulation of lattice defects leads to decreasing values. The decrease of the modulus of elasticity in the near-surface layer is an indication of the plastic strain being larger than in the rest of the cross-section. After reduction to 6.13 mm, strain was probably distributed uniformly across the cross-section.

Schrank [12] points out the difficulties in evaluating rotary swaging. In [12], the effect of the feed angle φ is analysed in detail. This angle indicates the relative rotation between the wire and the swaging dies between two blows. Another parameter is the entrance angle of the swaging die, which is typically 3.5°.

V. Summary of Results

Wires of commercial-purity titanium grades 2 and 4 were produced in rotary swaging trials. Starting bars were progressively reduced to 3.81 mm which corresponds to a total true strain of 2.2. It was demonstrated that:

- grain size becomes finer on the transverse section and grains become elongated on the longitudinal section;
- titanium grade 2 shows better work hardening during cold deformation than titanium grade 4;
- in both materials under test, rotary swaging causes more appreciable strengthening in the centre of wire. This fact is documented by the hardness profile across the cross section.

Acknowledgment

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