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Continuous extrusion of commercially pure titanium GRADE. 4

J. Palan*, J.V. Taboada, T. Kubina, L. Malecek, J. Hodek
COMTES FHT a.s., Průmyslová 995, Dobřany 334 41, Czech Republic
* Corresponding e-mail address: jan.palan@comtesfht.cz

ABSTRACT

Purpose: Continuous extrusion of metals using Conform™ machine is used to introduce severe plastic deformation and to improve mechanical properties of metals by reducing their grain size. This paper describes a development of a continuous extrusion sequence for Ti grade 4 in the CONFORM 315i machine.

Design/methodology/approach: The influence of material flow conditions on the surface quality of final extruded rods was analyzed with the FEM-based DEFORMTM software.

Findings: During the development, several process parameters were varied, such as the die chamber temperature and the extrusion velocity.

Research limitations/implications: The goal was to conduct the experiment at the lowest possible temperature in order to achieve a maximum strain hardening effect. The material's mechanical properties and its flow through the die chamber were studied. The homogeneity of the material flow and the surface quality of final rods were then optimized.

Originality/value: The effort led to improvements in the analytical model used in the FEM simulation so that the surface quality can now be optimized more efficiently.

Keywords: FEM simulation; Continuous extrusion; Titanium; SPD; Conform™; DEFORMTM; Grain size

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Analysis and modelling

1. Introduction

The plastic deformation behaviour of metals and its effect on grain size (d) have been a subject of extensive research for a long time. Recently, this topic has become even more attractive due to the introduction of ultrafine-grained (UFG, d<~500nm) and nanocrystalline (NC, d<100nm) materials [1,2].

The research into SPD (Severe Plastic Deformation) processes is mainly focused on grain refinement where material properties are governed by the Hall-Petch equation. Conventionally processed industrial metals typically have a grain size in the range of 10-50 μm. Reducing the grain size from 10 μm to μm can increase the yield strength of metals by more than 100% [3-5].

In metal-forming processes, the presence of high hydrostatic pressure combined with high values of shear strain is essential for producing a high density of lattice defects, particularly dislocations. This can result in significant grain refinement and improvement in mechanical properties. The grain refinement usually occurs in a multi-step process (i.e. multiple passes of the material through a forming tool are necessary) [3].

The making of ultrafine-grained metals is often associated with the ECAP (Equal Channel Angular Pressing) method [3]. However, this method is not suitable for processing large volumes of metals, since it is based on repeated pressing of a small specimen through a special extrusion die. Thus, recent research efforts have been focused on developming continuous processes based on ECAP. The present experiments were performed on the Conform machine (Fig. 1) which is often used for continuous extrusion of aluminium and copper profiles on an industrial scale [6].

The Conform machine (see Fig. 1) consists of a wheel with a channel through which the input material is fed into the die chamber by the wheel's rotation. The die chamber is located in the output section installed on the wheel, where sufficient pressure and heat are generated for extrusion [7].

The Conform process was analyzed theoretically by Green [6] and Etherington [8]. Peng [9] made an investigation into the material flow during the Conform process using lead as the feedstock material. A 2D finite element model for Conform extrusion of copper was published in 1993 by Reininkainen [10]. Recently, Velay [11] and Cho [12] used a full 3D finite element model to examine Conform extrusion of aluminium. In the present study, continuous extrusion of titanium was simulated using the FEM software DEFORM-3D. An important goal was to accurately measure the required data and to implement them in the FEM model. The results provide a theoretical background for further development of the conform process.

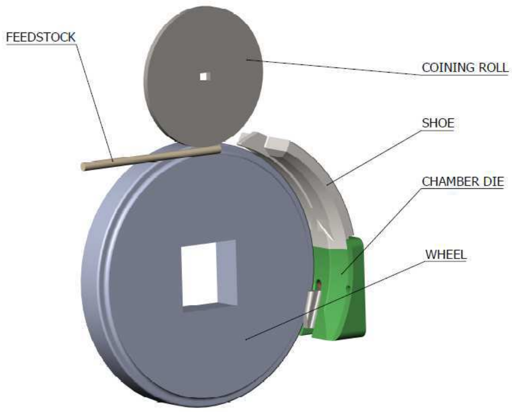

Fig. 1. Description of the 3D model of Conform process

2. Experiment

Input feedstock of Ti grade 4 in the form of bars with a diameter of 10 mm was used. The chemical composition of the experimental material is shown below.

Table 1.
Chemical composition of the experimental material (weight %)

	Fe	O	C	H	N
CP-Ti gr. 4	0.5	0.4	0.1	0.0125	0.05

2.1. FEM model

Thanks to mirror symmetry, only one half of the tooling and feedstock could be analyzed in the FEM model. The entire model incorporated the influence of thermal stresses. The titanium feedstock was considered as a plastic body, whereas the rest of the model was considered to consist of rigid bodies. The friction coefficient between the titanium feedstock and wheel was set to μ=10. In the die chamber, the friction coefficient was set to μ=0.7 [13].

Temperature fields were calculated for both the titanium feedstock and the wheel. The other components were assumed to have a constant surface temperature. The heat transfer coefficient α between the wheel and the titanium feedstock was set to $1000 Wm^{-2}K^{-1}$ as the default value [13].

In the input section, both velocity and temperature were calculated. Theoretically, the heat transfer between the channel surface and the wheel can be derived from Fourier's law as:

$$q_m = h_c \cdot (T - T_m) \tag{1}$$

where T_m is the wheel temperature and h_c is the heat transfer coefficient.

2.2. Extrusion process

The Conform extrusion process is defined by several parameters, such as temperature, material properties, wheel speed and others. The most complex challenge is accurate temperature measurement. It was carried out on the main parts of the Conform machine (the abutment, die chamber, wheel and motor). An example plot of all temperature curves acquired in the process is shown in Fig. 2:

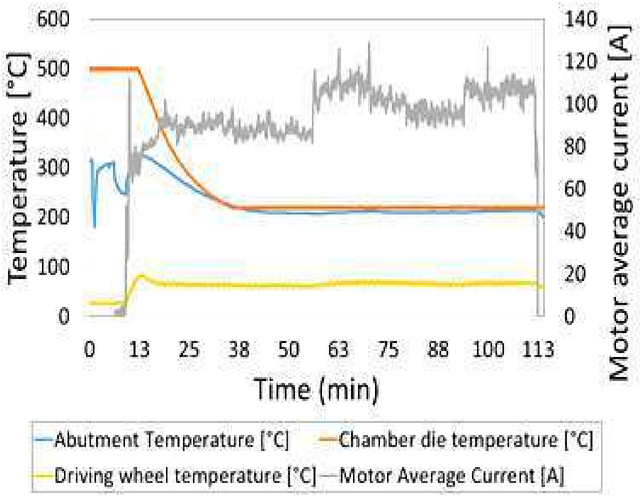

Fig. 2. Temperature curves for the main parts of the Conform machine during extrusion as measured by thermocouples

The die chamber was pre-heated to 500°C and, after holding for 20 minutes, it was slowly cooled down to 220°C. The abutment was also pre-heated up to 220°C. Stabilization at an almost constant temperature (around 210-220°C) was achieved after approx. 40 min in both die chamber and abutment. After this time, the process was stable. The beginning of each new pass can be seen in Figure 2 as a rise in the motor current caused by the material's hardening due to severe plastic deformation.

3. Results and discussion

3.1. Numerical simulation of material flow

The FEM simulation results show that the material flow is non-uniform during the extrusion process. Due to the friction between tools and material, the flow rate is higher in the central part than on the wire's surface. Further, Figure 3 shows deceleration of the material flow in the upper part of the die chamber. This effect is caused by the filling of the gap between the wheel and the chamber die.

This phenomenon is more precisely illustrated in Fig. 4 using the point tracking function. Figure 5 shows surface defects (cracks) occurring on the upper side of the extruded wire due to tensile stresses resulting from the non-uniform material flow rate.

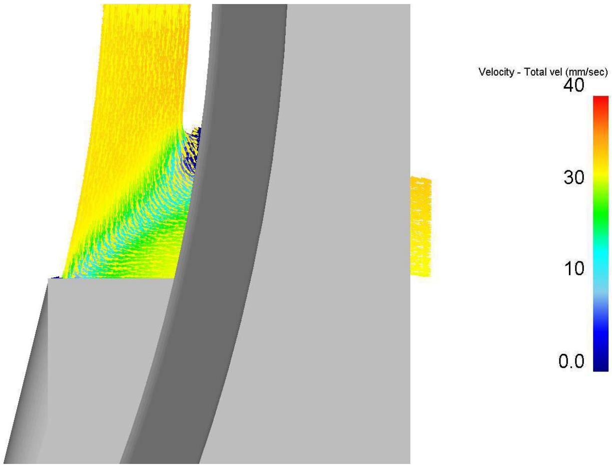

Fig. 3. Material flow in the gap between the wheel and the chamber die

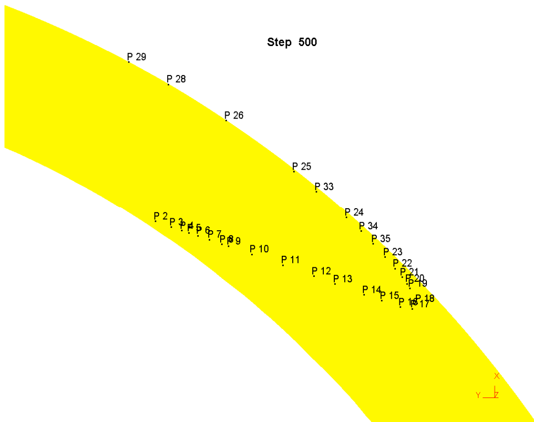

Fig. 4. Material flow rate distribution during extrusion

Fig. 5. Damaged surface on the upper side of the extruded wire

Due to the above-described effects, the resulting effective strain is not homogeneous (Fig.6). Higher values are achieved in the area of contact with the tools, where the material is deformed more intensively (Fig. 7).

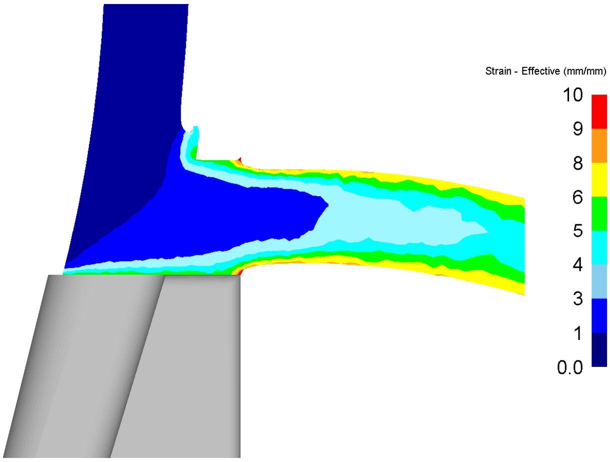

Fig. 6. Effective strain distribution

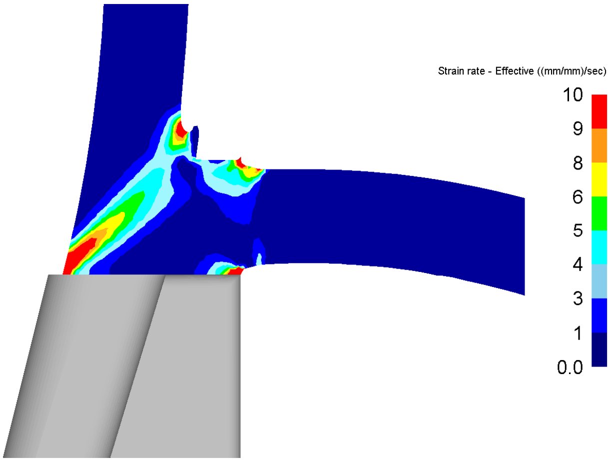

Fig. 7. Strain rate distribution

3.2. Mechanical properties

Mechanical properties of the extruded wires were measured after each pass. As expected, the Conform process leads to a significant enhancement of strength, whereas the ductility (measured as A_5 values) remains nearly unchanged thanks to grain refinement. The most significant increase in mechanical properties occurred after the first pass when the ultimate strength (R_m) increased from 651 MPa to 749 MPa. The results are given in Table 2.

Table. 2.
Mechanical properties of Ti gr. 4 upon Conform process

	$R_{p0.2}$	R_m	A_5	Z
	MPa	MPa	%	%
Feedstock	563	651	24	51.7
First pass	706.9	749	22	55.4
Second pass	740	760	22	60.2
Third pass	756	773	23	64.4

3.3. Microhardness

In order to analyze the effect of non-uniform strain distribution on local mechanical properties, microhardness profiles were measured across the cross-section of the extruded wires. For this measurement, wires after three passes were used, in which optimum grain refinement was expected. The measured microhardness profile is shown in Fig. 8.

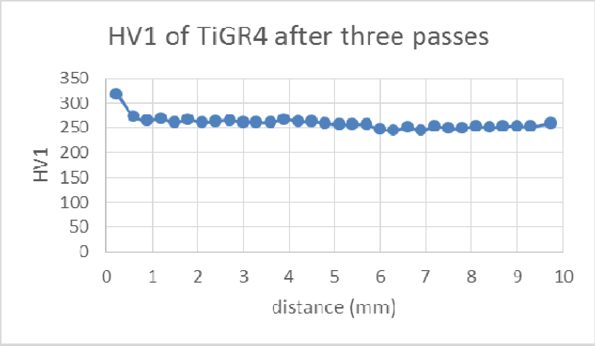

Fig. 8. Micro-hardness profile (after 3 passes)

The left part of the diagram (distance 0 mm) represents the upper part of the output wire, where the material flow slows down as the gap between the wheel and the die chamber is filled. Thus, the strengthening effect is most significant in this area.

4. Conclusions

The material flow during the Conform process of Ti gr. 4 was analyzed. Attention was focused on grain refinement and improvement in mechanical properties by means of the process. It was found that non-uniform material flow leads to local surface degradation of the output wires. This effect was confirmed by both FEM analysis and experimental verification.

A significant impact of severe plastic deformation imparted by the Conform process upon mechanical properties of Ti gr. 4 wires was demonstrated. From this point of view, the first pass is the most important step, in which the yield strength increased by 25%. Ductility (represented as A_5 elongation) was not affected by the Conform process.

Thanks to the non-uniform material flow, the effective strain in the surface is significantly higher than in the central part of the wire. However, after 3 passes, the mechanical properties become quite homogeneous across the entire cross section of the wire.

Acknowledgements

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