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Changing the rheo-mechanical models of light metal Ti and Ti-alloy powders under uniaxial compaction

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Abstract. On the basis of uniaxial compacting process the authors have examined the rheological and mechanical properties of light metal Ti and Ti-alloy powders as function of forming pressures and times. For the examination of the compacting properties and create the rheo-mechanical model a special uniaxial instrument was developed and used by the authors. To determine the time dependence behavior of these light metal alloy powders a combine rheo-tribometer was used which was patented, developed and produced by IGREX Ltd. in Hungary. Using these two instruments the authors could successfully illustrate how the rheological models of light metal Ti and Ti-alloys are changed depending on forming pressures and times of loading forces.

In this work the rheological behaviors and models of different Ti alloys are shown as function of compaction times and pressures. The values of modulus of elasticity of Voight-Kelvin and Hooke components as well as values of viscosity of the viscous-plastic components are also determined and given by the authors.

1. Introduction

In our days rheology is playing very essential role in different segments both of biology and human life [1-8], industrial technology [9-20] and materials science [21-30]. The physical, mechanical and rheological properties of raw, semi finished and finished materials are very important in development of new materials for different applications [31-34]. The rheological properties are playing especially important role during forming and compacting materials under pressures [35-42].

The powder compacting technology is one of the most efficient forming technologies not only in ceramic industry [43-47] but in metallurgy [48-53] and machine industry [54-58] also. In ceramic industry to prepare units and parts from powders with increased physical and mechanical properties very often high temperature pressing [59-60], isostatic pressing [61-63], hot isostatic pressing or compaction under high speed mechanical forces and shock-waves [64-66] are used. The powder pressing technology is especially popular in production of electrical components [67] and machine parts not only with axis-symmetrical shapes but with complicated geometrical forms. At the same time to make metallic machine elements and parts with the required final geometrical parameters are impossible without understanding the changes of rheological and mechanical properties of the used metal powders during the pressing processes.
2. Materials and experiments
The knowledge of rheological properties of titanium alloy powders and flakes is necessary to interpret the processes occurring in materials during their compacting and understand the changes of geometrical sizes of the manufactured pre-compacted specimens after their compaction.

For rheological tests the titanium alloy powders were obtained from IPAX Ltd. and the tests were realized on a 100 kN mechanical pull-press. Thus, it was possible to compact cylindrical specimens with diameter of \( D = 15 \) mm, providing static compaction of titanium alloy powders according to the principle shown in Fig. 1. During the compacting the compression pressures were linearly increased and kept by 10 seconds at pressure values of 10MPa, 100MPa, 150MPa, 200MPa, 250MPa, 300MPa, 350MPa and 400MPa. The results of load-displacement (pressure-compaction) values were recorded automatically in diagrams on computer (11).

It is well known from the literature [37, 68-71] that the rheological properties and parameters of materials can be determined from the deformation-time curves taken at different shear stresses and rates. To determine rheological parameters of pre-compacted specimens made from different titan alloy powders the combined rheo-tribometer of IGREX Ltd was used. The schematic outline of this apparatus is shown in Figure 2.
3. Results and discussions
The compaction displacement (deformation) as function of load pressures were taken on the rheology measuring device (Fig. 1) and were recorded automatically in diagrams (Fig. 3) on the computer. The analyze of these diagrams shows that the compacting process of the titan alloy powders and flakes is starting with the filling of the compacting die cavity thanking to the arrangement of the powder grains after closing the die cavity. This intensive compaction is continuing until the compression pressures are reaching the values of 8-10MPa. Such behavior of alloy powders can be described with Maxwell's rheological material model. Because of the intensive compacting process at low compression pressures of the titanium alloy powders in the cavity of the dies, approx. 25% of bulk density growths are taken place under the above low compacting pressure. Despite of the significant compaction, however, the examined titanium alloy powders have flown away from the compacting die after withdrawn the lower punch.

![Figure 2. Scheme of combined rheo-tribometer](image)

Figure 2. Scheme of combined rheo-tribometer
1-instrument table, 2-small drive, 3-electric motor, 4-cable drum, 5-cableway, 6-batching car (with the shearing plate), 7-inductive displacement detector, 8-force-meter (spider), 9-heatable specimen holder, 10-pneumatic power cylinder, 11-magnetic valve, 12-pressure gauge, 13-compressor, 14-thermostat, 15-control unit, 16-data recorder (spider 8), 17-computer (capturing and processing data)

![Figure 3. Compaction displacement (deformation) as function of load pressures](image)

Figure 3. Compaction displacement (deformation) as function of load pressures
1 - powders of titanium sponge, 2- Ti50Ni alloy powders, 3- Ti6Al2.5Fe
From the diagrams obtained, it can be seen well that with the maintenance by 10 seconds the different pressing pressures the compression processes continuing thanking to the decreases of gaps between the powder particles. This kind of compaction of the granules is demonstrating a non-elastic deformation as function of time.

From the achieved compaction displacement (deformation) curves (Fig. 3) it is easy to recognize that in case when the values of loaded pressures are above 8-10MPa, the compacting process consists of the following three relatively distinct sections.

A. At this stage of the compaction the grains of titanium alloy powders are arranged in the cavity of the compacting die, the majority of the volumes of gaps ( pores ) between the particles are disappearing step by step and the degree of compactness or specific deformation reaches 70-75% of the total final compaction. After removing the lower and upper punches, the pre-compacted specimens remains in the compacting die cavity thanking to the accumulated elastic energy of the metallic particles and pressured airs in the gaps ( pores ) between the grains. At this stage of compression the degree of the residual deformation is so great that in the rheological model viscous and "quasi-plastic" parts must be present together with the elastic components to characterize the mechanical properties of the material. At this stage of compaction however the compacted pre-compacted specimens cannot be removed without disruption. When the compacting pressure less than 100MPa the titanium alloy powders of pre-compacted specimens will be dissipated during removing from the compacting die cavity due to the shear stress generated by the friction force between the surfaces of die cavity and the granules. Due to this phenomenon and to the significant compaction observed at this stage the deformation properties of the titanium alloy powders can be characterized by the rheological model shown in Figure 4 (A).

B. At this stage of the compaction the granules of the titanium alloy powders are further arranged in the compacting die cavity the volumes of gaps ( pores ) between the particles continue to decrease or a substantial part of the particles are disappeared. The degree of compactness or specific deformation reaches 95-97% of the total final compaction. In this stage the pre-compacted specimens remains in the compacting die cavity not only after withdrawn the lower and upper punches, but about 50-60% of the weight of the pressed rods will stay together after remove it from the die cavity. At this stage of compacting the deformation properties of titanium alloy powders can be characterized with rheological model given in Figure 4 (B). In this case the titanium alloy powders behave as a "parallel" plastic viscous body in line with a parallel viscous-elastic Voight-Kelvin's "body", giving a Burgers type of rheological model.

C. In the last stage of compaction, the granules of the titanium alloy powders in the compacting die cavity are settled only by destruction of the grain particles; the "permeable" gaps between the particles disappear as they become " pores " or " capillaries " . The compression and specific deformation of particles are already not intense and very small and they reach nearly 100% of the available compression. The pre-compacted specimens can be taken out from the compacting die cavity without injury and surface defects, meanwhile leaving the die cavity their geometric dimensions are immediately increased measurably thanking to the elastic deformation of the alloy particles. At the same time the geometrical sizes of the pre-compacted specimens are growing continuously during in a few hours after the pressing. Because of this deformation properties of specimens in the final compression stage the rheological properties of titanium alloy powders can be characterized by Figure 4 (C). In this stage of compacting the titanium alloy powders behave themselves like an "elastic-plastic-viscous body" thanking to the destructed particles under pressure and a viscous-elastic Voight-Kelvin's body of the non-destructed particles.
The rheological equation of materials having rheological model as C in Figure 4 is well known in the literature [68, 69, 71 and 72]. Its general form is:

\[ \tau(t) = \tau_0 + \eta_1 \dot{\varepsilon} + \eta_1 t_r \ddot{\varepsilon} - \dot{t} \left( t_{fr} + t_r - t_{fr} \cdot t_r \frac{\eta_1}{\eta_2} \right) t_{fr} t_r \dot{\varepsilon} \text{ [MPa]} \]  

Where:
- \( \tau(t) \) – time dependent shear stress developed in the material during compaction [MPa];
- \( \tau_0 \) – the static yield point [MPa];
- \( \dot{\tau} \) – the first derivative of the shear stress [MPa.s\(^{-1}\)];
- \( \ddot{\tau} \) – the second derivative of the shear stress [MPa.s\(^{-2}\)];
- \( \eta_1 \) – viscosity of the plastic-viscous body [MPa.s];
- \( \eta_2 \) – the elasticity modulus of the Voight-Kelvin test [MPa.s];
- \( \dot{\varepsilon} \) – the first derivative of the deformation developing in material or shear rate[s\(^{-1}\)];
- \( \ddot{\varepsilon} \) – the second derivative of the deformation developing in the material or first derivative of shear rate [s\(^{-2}\)];
- \( t_r \) – the delay time of the elastic deformation in the material [s];
- \( t_{fr} \) – the time of relaxation of mechanical stresses in material [s].

The combined rheo-tribometer of IGREX Ltd (Fig. 2) was used to determine the rheological parameters of pre-compacted specimens made from different titan alloy powders. The deformation-time curve of Ti50Ni alloy powders at 3.5MPa normal pressure and 72N car moving force is shown in Figure 5.
The rheological equation (Eq.1) is capable to characterize complexly the mechanical process in the titanium alloy powders during their uniaxial compacting. The parameters of equation (Eq.1) were determined experimentally on the combined rheo-tribometer and it provides a corresponding answer to the mechanical state and behavior of powders during their uniaxial compacting in the die cavities and the pre-compacted specimens after they leave the die (Table 1).

### Table 1. The parameters of equation (1) measured by combined rheo-tribometer

| The measured parameters                                      | Ti sponge powder | Ti50Ni alloy powders | Ti6Al2,5Fe alloy powders |
|-------------------------------------------------------------|------------------|----------------------|--------------------------|
| Specific Hooke deformation; $Y_R$ [-]                       | 0.075            | 0.225                | 0.68                     |
| Specific elastic deformation; $Y_E$ [-]                     | 0.035            | 0.070                | 0.090                    |
| Specific plastic deformation; $Y_{pl}$ [-]                  | 0.615            | 1.150                | 0.360                    |
| Specific yield deformation $Y_0$ [-]                        | 0.110            | 0.295                | 0.158                    |
| Static yield stress $\tau_0$ [MPa]                          | 0                | 0                    | 0                        |
| The instantaneous shear stress determining the elasticity modulus of the Hooke body: $\tau_{inst}$ [MPa] | 0.188            | 1.907                | 0.179                    |
| The elastic shear stress determining the elasticity modulus of the Voight-Kelvin body: $\tau_{elast}$ [MPa] | 0.122            | 0.170                | 0.167                    |
| The elastic module of Hooke body; $E_1$ [MPa]               | 2.510            | 8.474                | 2.630                    |
| The elastic module of Voight-Kelvin body; $E_2$ [MPa]       | 3.495            | 2.423                | 1.859                    |
| The viscosity of the plastic-viscous body; $\eta_1$ [MPas]  | 1.399            | 4.860                | 1.592                    |
| The viscosity of the Voight-Kelvin body; $\eta_2$ [MPas]    | 0.020            | 0.371                | 0.019                    |
| The slope of the plastic deformation; $\alpha$ [°]          | 5°               | 2°                   | 6°                       |
| The slope of elastic deformation; $\beta$ [°]               | 84°              | 79°                  | 84°                      |
| Shear rate in the broken material structure; $v_1$ [1/s]    | 0.087            | 0.035                | 0.105                    |
| Shear rate in the non-destructed material structure; $v_2$ [1/s] | 9.514            | 5.145                | 9.514                    |
| The delay time of the elastic deformation in the material; $t_r$ [s] | 0.557            | 0.573                | 0.605                    |
| Relaxation time of mechanical stresses in material; $t_\sigma$ [s] | 0.014            | 0.076                | 0.012                    |

### 4. Conclusions

The time and pressure dependencies of rheological behaviors and models of different Ti alloys are shown in this work. A rheological equation (Eq.1) and the values of elasticity modulus of Voight-Kelvin and Hooke components as well as values of viscosity of the viscous-plastic components are also determined and given by the authors in the presented work. With this work the authors contributed considerable to develop and establish the powder technology of light metal alloys in Hungary.

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