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EXPERIMENTAL ESTIMATION OF MAXIMAL DUCTILITY AND FLOW CURVES OF TITANIUM ALLOYS WITH HOT-TORSION TESTS

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ МАКСИМАЛЬНОЇ ПЛАСТИЧНОСТІ ТА КРИВИХ ЗМІЦНЕННЯ ТИТАНОВИХ СПЛАВІВ ЗА ДОПОМОГОЮ ВИПРОБУВАНЬ НА ГАРЯЧЕ КРУТІННЯ

Purpose. The purpose of this work is to clarify the temperature-deformation modes of pressing pipes of titanium alloys (VT1-0, PT-7M, VT-14, VT-15, TS-5 and TS-6) and to determine the regression coefficients of the Hansel-Spittel equation by investigating plasticity and the deformation resistance during hot rotation of the specimens.

Methodology. Studies on torsion were performed on a torsion test machine with a horizontal electronic force meter, with a maximum torque of $100 \text{ H} \times \text{m}$, temperature. The maximum temperature of the test specimens was 1250°C . Active capture of the test machine has a smooth rotation control from 5 to 200 rpm. Applying specimens with different aspect ratio to the length of the workpiece obtained a range of change of strain rates from 0.25 to 20 s^{-1} .

Findings. The main results of the study should be considered experimentally determined curves of the torque dependence on the angle of rotation of the sample to change the resistance of deformation of the metal, which allowed to clarify the temperature interval of maximum ductility during pressure treatment for alloys VT1-0, PT-7M, VT-14, VT-15, TS-5 and TS-6. Based on the data obtained on the deformation resistance, the coefficients of the Hansel-Spittel equation, which can be used to quantify the resulting stress in numerical simulation using the finite element method, have been statistically calculated.

Originality. The data on experimentally determined regularities of influence of temperature-deformation modes of torsion on the change of the value of deformation resistance, which is characteristic of conditions of hot pressing of pipes, have been further developed. This allows to predict the power parameters of the deformation process, as well as to select the press equipment and improve the productivity of the press line.

Practical implications. Studies on torsion have allowed to determine rational temperature-speed parameters of the process of pressing pipes from titanium alloys VT1-0, PT-7M, VT-14, VT-15, TS-5 and TS-6, for capacities of Ukrainian enterprises.

Key words: titanium, deformation, torsion, torque, temperature, strain rate, strain resistance, extrusion, tube.

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Introduction. Manufacturing of seamless tubes due to the complex strain-stress state in deformation zone requires not trivial approaches to accounting of changes of metal properties [1, 2]. In this case prescribing of strain, temperature and speed parameters at hot tube extrusion can be based on results of hot-torsion tests [3 – 5]. This method using the torque, obtained at test procedures, makes it possible to get a complete picture of the metal flow developing in conditions of prevailing shear deformation. The shear strain, calculated from torque curves, is used as an indicator of transition to plastic area and consequent failure [6].

Materials and research methods. The objective of presented study is a quantitative analysis of both strain and stress coordinates of the torque at hot-torsion tests. This analysis is based of position of M_{Cr} on the torsion test diagram (Fig. 1).

Figure 1 shows the typical diagram of hot torsion. These “torque versus angle” diagrams allow to trace change of the torque as a marker of shear stress as well as the shear strain in the specimen.

Fig. 1. Typical diagrams for torsion tests without securing the passive grip of the machine

“Torque versus angle” diagram, presented on the Fig. 2 show three major characteristic sections of change in torque:

1. First section is characterized by an increase of the torque. This quite narrow stage reflects the metal hardening before the transition to plastic flow. The maximal value of the torque (M_{Max}) means reaching of the flow stress in the specimen being tested.

2. Second section, which is characterized by a smooth almost linear decrease of the torque. Metal flows here with help of the dynamic return mechanism with cross slip or creep of dislocations [7] until reaching of the limit of ductile behavior, as evidenced the critical Moment (M_{Cr}).

3. In the Third section an intensive decrease of the torque can be observed. It ends with a specimen failure.

Therefore, the area of ductile behavior of metal is limited by only the second section. The coordinates of M_{Cr} point are significantly depending on temperature and stain rate. It means that both components of that coordinate (strain and stress) should be estimated for current temperature and strain rate. We'll present and analyze the results of such estimation for described in the Table 1 alloys consistently: first strain and then – stress.

The hot-torsion tests were performed on a testing machine SMEG-10T (torsion machine of the horizontal type with a maximum torque 100 Nm, equipped with a heating chamber). The temperature of the samples during the tests was in range of 800...1250 °C. Active grip of testing machine provides an adjustment of speed from 5 to 200 rpm. Passive grip has not been secured to make the specimen be able to change its length during the testing freely. It is intended to eliminate an occurrence of additional axial stresses.

Fig. 2. General view of specimen for torsion testing (a) and scheme for determining of the torsion angle φ (b)

Table 1. Chemical composition of studied titanium alloys according to OCT 1.90013-81 [8]

Alloy grade	Ti	Al	Mo	V	Zr	Cr	Sn	Other
BT1-0 (VT1-0)	99,472	-	-	-	-	-	-	0,528
BT14 (VT14)	89,55	4,9	3,2	0,9	-	-	-	1,45
BT15 (VT15)	78,568	2,7	7,5	-	-	10,2	-	1,032
TC5 (TS5)	85,67	5,2	-	2,1	2,7	-	3,3	1,03
TC6 (TS6)	73,72	2,95	4,1	6,7	0,75	10,8	-	0,98
ПТ7-М (PT7-M)	94,434	2,1	-	-	2,5	-	-	0,966

Research results. Estimation of critical strain.

Although the torsional deformation is not monotonous, the degree of shear strain according to [9, 10] can be calculated:

$$\Lambda_{Cr} = tg \varphi, \quad (1)$$

where φ – tilt angle of the artificial stress concentrator (notch) on the specimen (PQ line at fig. 2(b)).

When it is allowed what the distribution of strain along the length of the specimens is monotonous, critical shear strain (1), which leads to the failure can be represented as:

$$\Lambda_{Cr} = \frac{2\pi \cdot r \cdot n}{l}, \quad (2)$$

where r – specimen radius, mm; n – number of rotations until reaching the M_{Cr} ; l – specimen length, mm.

A general view of the specimen used in the

tests is shown in Figure 2.

The strain rate was determined by the following equation:

$$\dot{\varepsilon} = \frac{\pi \cdot r \cdot N}{30 \cdot l}, \quad (3)$$

where N – revolving speed, rpm.

Using specimens with a different ratio of radius to the length of the working part, were obtained the range of the strain rates from 6 to 25 s⁻¹.

The results of the torsion tests of specimens made of above-mentioned alloys are performed in the form of graphical dependences of the critical shear deformation on temperature, a characteristic view of which is shown in Figure 3. Such performance allows to find temperature range for each alloy where its ductile behavior exists longer. That statement assumes that the higher M_{cr} , the higher strain until it is reaching.

a

b

Fig. 3 a, b. Graphic dependences of the degree of shear strain on the test temperature: a – VT1-0; b – VT14

Fig. 3 c, d, e, f. Graphic dependences of the degree of shear strain on the test temperature: c – VT15; d – TS5; e – TS6; f – PT7-M

According to the graphical dependences (Fig. 3), it is possible to determine the temperature ranges of maximal length of $M_{Max} - M_{Cr}$ line at metal forming of the studied alloys. Thus, the longest life of ductile behavior can be observed at followed temperature range:

- VT1-0 – 900...1000 °C. Maximal ductility interval moves in low temperatures area at strain rate 25,2 s⁻¹;
- VT14 – 1050...1150 °C. The highest ductility at strain rate 6,28 s⁻¹ can be observed at temperature 1100 °C. Increase of strain rate to 25,2 s⁻¹

doesn't lead to change in ductile properties;

- VT15 – 1000...1100 °C. Elevation of strain rate leads for constant increasement of ductility of this alloy;

- TS5 – 950...1100 °C. This alloy shows almost insensible behavior on changing the strain rate in studied temperature range;

- TS6 – 1150...1200 °C. Its ductile behavior is similar to VT15;

PT7-M – 1000...1050 °C. This alloy similarly to TS5 is not sensible to changing the strain rate in studied temperature range.

Estimation of flow stress. It is also known [11, 12] that modern high-efficiency technologies of metal forming require consideration of the properties of titanium alloys. This is because currently the rheological concept of plastic deformation is applied to process calculations. This concept is the basis for most finite-element programs for simulation of metal forming processes [13, 14]. These programs require input of the rheological properties of deformed material in form of a table or an equation. Such data is usually obtained experimentally under certain conditions, being as possible close to conditions of the deformation process [15 – 17].

One of the most used equations, describing the rheological properties of a material, in finite-element programs is a model in which followed equation is used to calculate the flow stress of a material. [12, 18]:

$$\sigma_f = Ae^{a_1 T} \varepsilon^{a_2} \dot{\varepsilon}^{a_3} e^{a_4/\varepsilon} (1 + \varepsilon)^{a_5} T e^{a_7 \varepsilon} \dot{\varepsilon}^{a_8} \dot{\varepsilon}^{a_9 T} \quad (4)$$

where σ_f – flow stress, ε – equivalent strain; $\dot{\varepsilon}$ – strain rate, T – temperature, A , a_1 , a_2 , a_3 , a_4 , a_5 , a_7 ,

a_8 , a_9 – coefficients, obtained during material testing in appropriate conditions.

Presented below results of hot-torsion experiments and its statistical processing are aimed to determine the regression coefficients of equation (4) which can be applied to calculation of parameters of seamless tubes extrusion for studied titanium alloys. Due to strain-stress state inside the extrusion container and its outgoing zone the flow stress might be determined using the value of the shear stress:

$$\sigma_f = \sqrt{3} \cdot \tau_s, \quad (5)$$

where τ_s – shear stress close outer surface of the test specimen under the torsion [19].

$$\tau_s = \frac{12 \cdot M_{Max}}{\pi \cdot D^3}, \quad (6)$$

where M_{Max} – maximum torque, N×m.

Statistical analysis of the data, performed on Fig. 3, allow to determine the coefficients of equation (4) which are necessary for subsequent theoretical (using numerical modeling) studies. These coefficients are given in the Table 2. The range of recommended applicability of the coefficients indicated in Table 2 are shown in Table 3.

Practical application of obtained data could be more convenient when flow stress will be performed as a strain-stress dependence. Thus, using coefficients from the Table 2 we drew graphs of the flow stress depending on the logarithm of extrusion ratio $\ln \lambda$. These graphs were built considering the best ductile behavior range, which are shown above, both for lower and upper temperatures of that range. The strain rate were 1, 10 and 20 s⁻¹ what is widely used in hot tube extrusion.

Table 2. The coefficients for equation (4)

Alloy grade	A	a_1	a_2	a_3	a_4	a_5	a_7	a_8	a_9
VT1-0	$7.5e^{38}$	0.01	1.54	0.34	0.12	-0.002	0.17	-0.0002	-14.03
VT14	$8.4e^8$	-0.01	3.26	-2.72	0.3	-0.005	0.3	0.002	-0.41
VT15	9.72	-0.002	0.27	1.67	0.02	0.0015	-0.17	-0.002	0.42
TS-5	0.032	-0.015	0.09	0.29	-0.08	0.0007	-0.02	-0.0004	3.23
TS-6	0.6	-0.003	1.08	0.15	0.04	-0.0002	-0.1	-0.0002	1.22
PT-7M	$4.5e^{39}$	0.01	1.22	-0.7	0.03	-0.003	0.32	0.0007	-13.98

Table 3. The interval of applicability of the coefficients from the Table 2 for equation (3)

Alloy grade	Temperature, °C	Logarithm of the extrusion ratio, $\ln \lambda$	Strain rate $\dot{\varepsilon}$, s ⁻¹	Figure
VT1-0	800...1200	0.06...8.85	0.1...20	a
VT14	900...1200	0.06...5.5	0.1...20	b
VT15	900...1200	0.06...9.45	0.1...20	c
TS-5	900...1000	0.06...7.3	0.1...20	d
TS-6	1000...1250	0.06...8.1	0.1...20	e
PT-7M	800...1200	0.06...9.3	0.1...20	f

Development of the flow stress presented in the Fig.4 varies for studied alloys. It's due to features of dynamical processes in structure, prescribed by the chemical composition. We didn't aim to study it deeply here. Nevertheless, we can recommend

planning the technology staying between lower and upper curves. Work close to upper border causes an elevation of the load and temperature, lower area increases risk of internal failures and microcracks [20, 21].

Fig. 4. Strain-stress dependences built using the coefficients from the table 2 according to the equation (4) for: a – VT1-0; b – VT14; c – VT15; d – TS5; e – TS6; f – PT7-M

Conclusions. 1. Based on results of hot tension tests the temperature range of metal forming with maximal duration of ductile behavior for studied was estimated for each of studied titanium alloy: VT1-0 – 900...1000 °C; VT14 – 1050...1150 °C; VT15 – 1000...1100 °C; TS5 – 950...1100 °C; TS6 – 1150...1200 °C; PT7-M – 1000...1050 °C.

2. The sensibility to strain rate at hot deformation was studied. It was found that it falls at temperatures of maximal duration of ductile behavior for majority of studied titanium alloys, excepting VT15 and PT7-M.

3. Using the statistical analysis of the results of

hot torsion tests coefficients for Hensel-Spittel equation for estimation of flow stress at hot deformation are found for studied titanium alloys. The range of recommended applicability of the coefficients is specified.

4. Flow curves of studied titanium alloys in temperature range of maximal duration of ductile behavior are built for widely used at tubes hot extrusion strain rate (1...20 s⁻¹).

5. Favorable ranges of “Strain – Strain rate – Temperature” combination, applying to the hot tubes extrusion are recommended.

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- Мета.** Метою даної роботи є уточнення температурно-деформаційних режимів пресування труб з титанових сплавів (BT1-0, ПТ-7М, BT-14, BT-15, TC-5 і TC-6) і визначення коефіцієнтів регресії рівняння Хензеля-Шпиттеля шляхом дослідження пластичності та опору деформації при гарячому крученні зразків.
- Методика.** Дослідження на кручення проводили на випробувальній машині для кручення з електронним силовимірювачем горизонтального типу, з максимальним крутним моментом 100 Н×м, температурна. Максимальна температура зразків при випробуваннях становила 1250 °С. Активне захоплення випробувальної машини має плавне регулювання обертів від 5 до 200 об/хв. Застосовуючи зразки з різним співвідношенням радіусу зразка до довжини робочої частини отримували діапазон зміни швидкостей деформації від 0,25 до 20 с⁻¹.
- Результати.** Основними результатами дослідження слід вважати експериментально визначені криві залежності крутного моменту від кута закручування зразка на зміну опору деформації металу, що дозволило уточнити температурний інтервал максимальної пластичності при обробці тиском для сплавів BT1-0; BT14; BT15; TC5; TC6; ПТ7-М. На підставі отриманих даних щодо опору деформації статистично розраховано коефіцієнти рівняння Хензеля-Шпиттеля, які можуть бути використані для кількісного визначення виникаючого напруження при чисельному моделюванні з використанням методу скінченних елементів.
- Наукова новизна.** Одержали подальший розвиток відомості щодо експериментально визначених закономірностей впливу температурно-деформаційних режимів кручення на зміну величини опору деформації, що характерно для умов гарячого пресування труб. Це дозволяє прогнозувати енергосилові параметри процесу деформації, а також обирати пресове устаткування та підвищити продуктивність пресової лінії.
- Практична цінність.** Дослідження на кручення дозволили визначити раціональні температурно-швидкісні параметри процесу пресування труб з титанових сплавів BT1-0; BT14; BT15;

ТС5; ТС6; ПТ7-М для потужностей українських підприємств.

Ключові слова: титан, деформація, кручення, момент кручення, температура, швидкість деформації, опір деформації, пресування, труба.

Цель. Целью данной работы является уточнение температурно-деформационных режимов прессования труб из титановых сплавов (BT1-0, ПТ-7М, ПТ-14, BT-15, ТС-5 и ТС-6) и определение коэффициентов регрессии уравнения Хензель-Шпиттеля путем исследования пластичности и сопротивления деформации при горячем кручении образцов.

Методика. Исследования на кручение проводили на испытательной машине для кручения с электронным силоизмерителем горизонтального типа, с максимальным крутящим моментом 100 Нм, температурна я. Максимальная температура образцов при испытаниях составляла 1250 °С. Активный захват испытательной машины имеет плавную регулировку оборотов от 5 до 200 об/мин. Используя образцы с различным соотношением радиуса образца к длине рабочей части получали диапазон изменения скоростей деформации от 0,25 до 20 с⁻¹.

Результаты. Основными результатами исследования следует считать экспериментально определенные кривые зависимости крутящего момента от угла закручивания образца на изменение сопротивления деформации металла, что

позволило уточнить температурный интервал максимальной пластичности при обработке давлением для сплавов BT1-0; BT14; BT15; ТС5; ТС6; ПТ7-М. На основании полученных данных по сопротивлению деформации статистически рассчитаны коэффициенты уравнения Хензель-Шпиттеля, которые могут быть использованы для количественного определения возникающего напряжения при численном моделировании с использованием метода конечных элементов.

Научная новизна. Получили дальнейшее развитие сведения о экспериментально определенных закономерностях влияния температурно-деформационных режимов кручения на изменение величины сопротивления деформации, что характерно для условий горячего прессования труб. Это позволяет прогнозировать энерго-силовые параметры процесса деформации, а также выбирать прессовое оборудование и повысить производительность прессовой линии.

Практическая ценность. Исследования на кручение позволили определить рациональные температурно-скоростные параметры процесса прессования труб из титановых сплавов BT1-0; BT14; BT15; ТС5; ТС6; ПТ7-М для условий мощности украинских предприятий.

Ключевые слова: титан, деформация, кручение, момент кручения, температура, скорость деформации, сопротивление деформации, прессование, труба.

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