THE FRACTURE TOUGHNESS OF FORGINGS AND STAMPINGS OF HIGH-STRENGTH TITANIUM ALLOYS

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High-strength titanium alloys are prospective materials for making rotors of centrifugal separators designed for treating media having a high chloride ion concentration. At the present time, six types are produced industrially in bulk [1]: VT6, VT14, VT3-1, VT15, VT16, and VT22, while the alloys VT23 and AT6 are being produced in test quantities. This article presents results of an investigation for the basis of selecting and using the optimum titanium alloy according to its properties to provide for high centrifugal machine reliability.

In accordance with the data in [2] in order to provide rotor strength the titanium alloys must possess $\sigma_u \geq 900$ MPa. Additionally, they must possess adequate ductility (δ = 8-10%). All the alloys listed above possess the required strength, but only the alloys VT6, VT3-1, and AT6 have the required ductilities (the highly ductile alloy VT16 is mainly used for bracket components [1]). These alloys have almost the same corrosion resistance in media containing chloride ions [3]. Therefore, the alloys VT6, VT3-1, and AT6 were investigated. Nevertheless, it should be noted that in the final choice of alloy for making separator rotors preference should be given to the material having the highest resistance to cracking. It must also be taken into account that high fracture toughness is a basic property of a material which provides for reliable rotor service [4]. The fracture toughness characteristics were determined on forgings and stampings, i.e., semifinished products from which the main rotor components are made. The chemical properties of the semifinished alloys tested are given in Table 1.

TABLE 1

Alloy	Semifinished product and dimensions, mm	Chemical composition, %										
		Al	V	Mo	Zr	Cr	Fe	Si	O	N	C	H
VT3-1	Stamping (740 × 80)	5,75	—	2,42	0,15	1,52	0,52	0,26	0,075	0,0i	0,02	0,030
	Forging (435 × 35)	6,00	—	2,43	0,14	1,86	0,42	0,13	0,10	0,05	0,10	0,001
VT6	Forging (435 × 35)	5,95	4,12	—	2,00	—	0,30	0,15	0,20	0,05	0,10	0,015
AT6	Stamping (660 × 360)	5,79	—	—	—	0,72	0,60	0,32	0,12	0,02	0,02	0,005
	Forging (550 × 100)	6,60	—	—	—	0,80	0,53	0,34	0,12	0,01	0,05	0,002

TABLE 2

Alloy	Semifinished product	Deforming temperature and heat-treatment conditions
VT3-1	Stamping	Stamping at 950°C ($\alpha + \beta$ range), cooling in air, isothermal annealing at 910°C, 2 h, cooling to 640°C, holding 2 h, cooling in air
	Forging	Forging at 940°C ($\alpha + \beta$ range), cooling in air
		Forging at 1040°C (β range), cooling in air
		Forging at 940°C ($\alpha + \beta$ range), isothermal annealing at 920°C cooling to 650°C, holding 2 h, cooling in air
VT6	Forging	Forging at 940°C($\alpha + \beta$ range), cooling in air, forging at 1040°C (β range) cooling in air, forging at 940°C ($\alpha + \beta$ range), cooling in air, annealing at 840°C, 2 h, cooling in air
AT6	Stamping	Stamping at 980°C, cooling in air, annealing at 850°C, 4 h, cooling in air
	Forging	Forging at 1050°C, cooling in air, annealing at 950°C, 3 h, cooling in air

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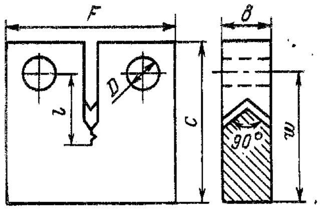

Test piece type	Test piece dimensions, mm					
	c	F	b	D	w	l
ST-1	62,5	60	30	12,5	50	27,5
ST-2	125,0	120	30	25,0	100	55,0
ST-3	188,0	180	75	38,0	150	82,5

Fig. 1

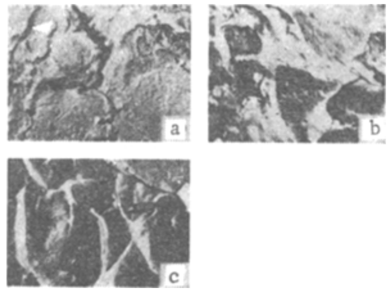

Fig. 2

Fig. 1. Design sketch and main dimensions of type ST test pieces.

Fig. 2. Fractograms for test pieces of various titanium alloys: a) alloy VT3-1 (stamping, see Table 2); b) alloy VT6 (forging at 940°C, see Table 2); c) alloy AT6 (forging, see Table 2).

TABLE 2

Alloy	Test piece type	$\sigma_{0,2}$	σ_u	δ	ψ	KCU	KCT	Scatter range of K_c, $N/m^{3/2}$	Mean value of K_c, $N/m^{3/2}$
		MPa		%		MJ / m²			
VT3-1	ST-2	1008	1038	17,9	35,4	0,39	0,12	(720,5÷802,6)10⁵	755,2·10⁵
		1021	1086	16,0	37,0	0,56	0,24	(790÷840,5)10⁵	815,3·10⁵
		995	1104	12,9	20,6	0,59	0,40	(935,4÷986)10⁵	954,3·10⁵
	ST-1	1030	1048	9,0	16,2	0,29	0,20	(761,5÷859,5)10⁵	802,6·10⁵
VT6	ST-2	912	982	14,6	35,3	0,51	0,35	(723,6÷1004,8)10⁵	872,0·10⁵
		980	1015	13,4	52,1	0,58	0,39	(628,8÷973,3)10⁵	777,4·10⁵
	ST-1	917	972	15,8	36,6	0,48	0,21	(616,2÷771,0)10⁵	701,5·10⁵
AT6	ST-3	887	907	13,0	29,6	0,73	—	(1121,8÷1125)10⁵	1121,8·10⁵
	ST-2	881	917	16,9	33,5	0,57	0,31	(1235,5÷1276,6)10⁵	1260,8·10⁵

It can be seen that the semifinished products had various initial compositions. The forgings of alloy VT3-1 and VT6 were made by in both the $\alpha + \beta$ and also in the β region. After forging, part of the material of these alloys was annealed. The heat-treatment conditions for the semifinished products are given in Table 2.

The main fracture toughness characteristics, the critical stress intensity factors K_{Ic}, were determined on test pieces in eccentric tension in accordance with the standard method [5, 6]. For this the test pieces were of type ST having the main dimensions as shown in Fig. 1. The testing was conducted on a model "Instron" machine.

The values of the critical load P_Q, corresponding to the start of unstable crack growth, were determined from the load/displacement diagrams by the 5% section method [6]. The values of the stress intensity factor K_Q corresponding to the critical load P_Q were calculated from the equation

$$K_Q = \frac{P_Q}{b\sqrt{w}} \gamma, \tag{1}$$

where γ is the dimensionless stress intensity factor determined from tables [7]; b and w are geometric dimensions (see Fig. 1).

The correctness of the values obtained for K_{Ic} were checked by means of known criteria [5, 8]:

$$b \text{ and } l \geqslant 2.5\,(K_Q/\sigma_{0,2})^2; \tag{2}$$

$$P_{max}/P_Q \leqslant 1,1; \tag{3}$$

$$\psi_0 \leq 1.5\%, \quad (4)$$

where P_{max} is the maximum test piece load as determined from the load/displacement diagram; ψ_0 is the relative transverse reduction of the section "net" of the test piece after fracture; l is a geometric dimension (see Fig. 1).

The mechanical characteristics of the test pieces were also determined. Tensile testing to determine $\sigma_{0.2}$, σ_u, δ, and ψ was carried out in accordance with All-Union State Standard 1497–73, and for impact bending to determine KCU and KCT in accordance with All-Union State Standard 9454–78. The test pieces were cut from the forgings and stampings in a tangential direction (consequently, the crack was oriented radically). Three to five test pieces of each material composition were tested. The test results are given in Table 3.

It should be noted that the conditions (2)-(4) were fulfilled for all the test pieces. Therefore, the values of K_Q calculated by Eq. (1) correspond to the critical stress intensities in plane deforming K_{1c}.

The test results showed that the fracture toughness of VT3-1 alloy after deforming in the $\alpha + \beta$ range is $K_{1c} \simeq 790 \pm 79 \cdot 10^5$ N/m$^{3/2}$. Deforming in the β range increases the fracture toughness by 15-20% and this is in agreement with the results in [9]. After β deforming there is also observed an increase in the impact ductility KCU and particularly of the crack-propagation work KCT. The fracture toughness of VT6 alloy forgings differs (independently of the deforming condition) in the considerable scatter ($K_{1c\,min} < 632 \cdot 10^5$ N/m$^{3/2}$; $K_{1c\,max} > 995.4 \cdot 10^5$ N/m$^{3/2}$). In this case no influence of the deforming condition on the value of K_{1c} was detected. The maximum fracture toughness for high property stability is possessed by the AT6 alloy (for forgings $K_{1c} > 1106 \cdot 10^5$ N/m$^{3/2}$, for stampings $K_{1c} \simeq 1264 \cdot 10^5$ N/m$^{3/2}$).

Fractographic investigations of the fractures (Fig. 2) showed that the fracture of AT6 alloy has a clearly defined "cup-shape" character typical for ductile fracture; the fracture of the VT3-1 and VT6 alloys are of the mixed "cup-shaped/grooved" form characteristic for a more brittle fracture.*

It is possible to determine the minimum value of K_{1c} necessary to prevent brittle fracture of a rotor from titanium alloys on the basis of linear fracture mechanics. The critical stress σ_{cr} corresponding to the start of brittle fracture in the presence of a surface semielliptic crack of depth l and length 2c may be determined from the equation given in [10]:

$$\sigma_{cr} = K_c \Big/ \sqrt{\frac{1.21\pi l_{cr}}{Q}}, \quad (5)$$

where Q is a crack shape parameter depending on the ratio $l/2c$; $l_{cr} = 5l_{min}$ is the critical crack depth [11]; l_{min} is the minimum dimension of a defect detectable by ultrasonic defectoscopy of a forging and a stamping. For titanium forgings and stampings the dimension of a reliably detectable defect $l_{min} \geq 1$ mm. Therefore, $l_{cr} \sim 5$ mm for titanium rotors.

It is well known that the danger of brittle fracture of a structure arises in these cases when the value of the critical stress does not exceed the yield point of the material, i.e., $\sigma_{cr} \leq \sigma_{0.2}$ [11]. In accordance with the data in Table 3 for the AT6 alloy the minimum value of the yield point is 881 MPa. It is known that cracks arising in structures may vary in shape from strongly elongated to circular, i.e., $0 < l/2c \leq 0.5$.

In the calculation we assume a mean value of the ratio $l/2c = 0.25$. In this case in accordance with [10] the value of the crack shape parameter Q = 1.25. Then on the basis of Eq. (5) and taking $\sigma_{cr} = \sigma_{0.2}$ we find that in order to prevent brittle fracture the AT6 titanium alloys for making centrifugal separator rotors must have a fracture toughness $K_{1c\,min} \geq 1090.2 \cdot 10^5$ N/m$^{3/2}$. However, since the values of $\sigma_{0.2}$ for the VT6 and VT3-1 alloys are higher than that for the AT6 alloy (see Table 3), the required values of $K_{1c\,min}$ for these alloys will also be higher.

Therefore, the properties of the AT6 alloy shows this to be more preferred and it may be recommended for use in separator construction.

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* The fractographic investigations were carried out under the guidance of M. B. Shapiro.

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