

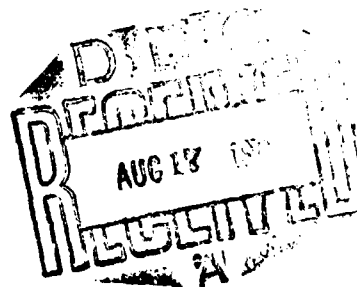
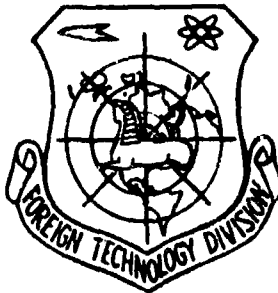
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VIBRATION STRENGTH OF CERTAIN STEELS AND OF TITANIUM-AND
ALUMINUM-BASED ALLOYS AT HIGH TEMPERATURES

by

G. S. Krivonogov, V. V. Matveyev, et al.



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13. ABSTRACT This work gives the results of investigating the damping properties of a number of materials either in use or very promising in the field of compressor blade manufacture; an analysis of their vibration strength is also given. As is known, the principal cause of destruction of compressor blades can be found in dynamic stresses. The risk from dynamic stresses is increased sharply owing to the high probability of corrosion-erosion damage during operation. [AR0101103]			

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VIBRATION STRENGTH OF CERTAIN STEELS AND OF TITANIUM- AND
ALUMINUM-BASED ALLOYS AT HIGH TEMPERATURES

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This work gives the results of investigating the damping properties of a number of materials either in use or very promising in the field of compressor blade manufacture; an analysis of their vibration strength is also given. As is known, the principal cause of destruction of compressor blades can be found in dynamic stresses. The risk from dynamic stresses is increased sharply owing to the high probability of corrosion-erosion damage during operation.

The following materials were investigated.

1. Martensitic chrome steel 1Kh12N2VMF (EI961) after oil-quenching from 1293°K and tempering at 953°K for 2 h.

2. Austenitic chrome-nickel steel Kh12N22TZMR (EP33 or EI696M), heat treated as follows: holding at 1273°K for 3 h, oil-quenching from this temperature, aging at 1023°K (16 h) and 923°K (16 h), cooling in air.

3. The titanium alloy VTZ-1 after isothermal annealing at 1143°K (1 h) + 923°K (2 h) and cooling in air.

4. The titanium alloy VT-8 after the following processing:
 - a) annealing at 1193°K (1 h) + 803°K (2 h) and cooling in air;
 - b) water-quenching from 1193°K and aging at 843°K (6 h).
5. The aluminum alloy AK4-1 after quenching from $803 \pm 5^{\circ}\text{K}$ (10 h).
6. The aluminum alloy VD-17 after water-quenching from 773° and aging at 443°K (16 h).

The damping properties of the materials were investigated in the uniform stressed state (longitudinal oscillation of specimens with round cross section) on a D-4 installation [4] and during pure bending on a D-7 installation [1] at normal and high temperatures. The divergence between the values of the logarithmic decrement obtained during longitudinal and bending oscillations is caused to a significant degree by specimen material and its thermal or mechanical treatment. Thus, in steel specimens whose final mechanical treatment (polishing) was carried out after heat treatment somewhat smaller values were obtained for the decrement with bending oscillations (on the average by 10-15%), while specimens which were heat treated (tempering) after polishing showed virtually identical decrement values.

The values of the decrement obtained for aluminum alloys during bending oscillations were approximately an order higher than those obtained during longitudinal oscillations. The divergence of the results is explained by the averaging of the dependence of the decrement on stress during bending oscillations due to the presence of a stress gradient over the volume and, mainly, by the different contribution to the total level of energy losses of the specimen surface layers with different forms of cyclic deformation. (During bending the surface layers of the specimen experience the greatest cyclic deformation; this is particularly significant during oscillations of thin specimens and for materials such as aluminum

alloys in which strong changes occur in the structure during thermal or mechanical treatment.) This indicates that along with determination of true characteristics of energy dissipation in the material in the uniform stress and structural states, for correct evaluation of the damping properties of parts operating under conditions of cyclic bending it is extremely important to study the dissipation of energy in the material during transverse oscillations of specimens treated according to the manufacturing technology of the working parts.

Examination of the experimental dependence of the logarithmic decrement of oscillations on the amplitude of maximum dynamic stresses σ_1 (during longitudinal oscillations) or σ_b (during bending oscillations) for the investigated materials at various temperatures (Figs. 1-4) indicates the following.

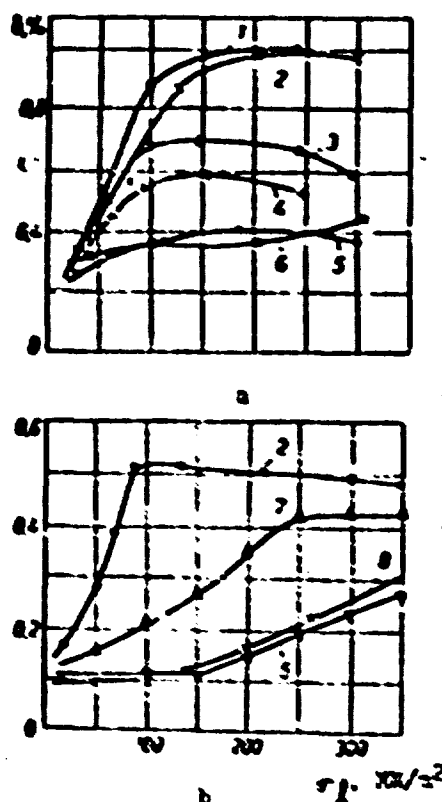


Fig. 1. Amplitude dependence of the decrement at various temperatures (tension - compression deformation): a - steel EI961; b - steel EI696N (1 - $T = 403^\circ\text{K}$; 2 - $T = 293^\circ\text{K}$; 3 - $T = 523^\circ\text{K}$; 4 - $T = 623^\circ\text{K}$; 5 - $T = 723^\circ\text{K}$; 6 - $T = 823^\circ\text{K}$; 7 - $T = 873^\circ\text{K}$; 8 - $T = 900^\circ\text{K}$).

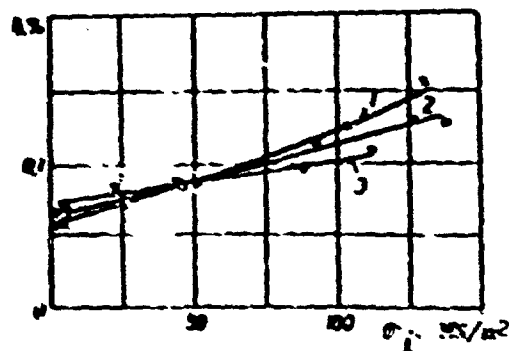
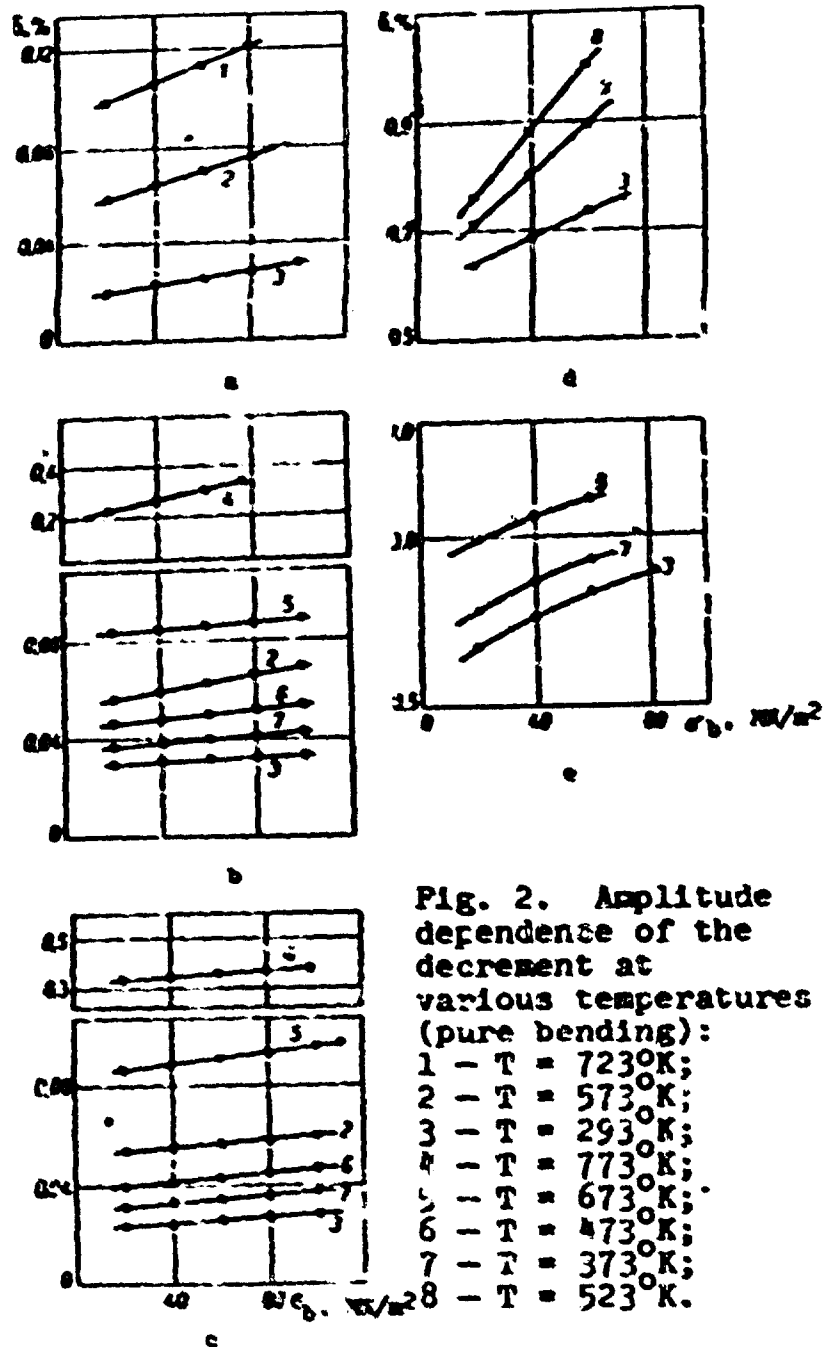
For martensitic steel EI961 the logarithmic decrement reaches 1% at room temperature; with an increase in temperature it drops, especially in the stress region above 100 MN/m^2 (Fig. 1a). At

a temperature of 823°K the decrement comprises only 40% of the initial value ($\sigma = 100 \text{ MN/m}^2$). This can be explained by the magnetomechanical nature of damping in this steel after sufficiently high tempering temperatures [3]. The decrement is somewhat higher than that at room temperature only at 403°K ; this is apparently connected with the presence of a relaxation peak in this temperature region. A further increase in temperature (above 823°K) is accompanied by a sharp rise in the value of the decrement.

For the austenitic steel EI696M at room temperature the logarithmic decrement first grows sharply with an increase in stress amplitude and then stabilizes at the 0.5% level (Fig. 1b). An increase in temperature leads to a weaker amplitude dependence and reduces the maximum achievable value of the decrement. On the basis of the positions of the dislocation theory of internal friction [2], it is possible to propose that at high temperatures there is a thermal breakaway of dislocations from the points of their attachment. As a result the number of dislocations participating in hysteresis motion during cyclic loading is reduced, which leads to a reduction in energy losses.

For the titanium alloys VT-8 (annealing, Fig. 2c and tempering + aging, Fig. 2a) and VTZ-1 (annealing, Fig. 2c) the decrement of oscillations depends weakly on the amplitude of stresses at all test temperatures; this is apparently connected with the strong attachment of dislocations during heat treatment, which ensures high strength properties in these materials. The decrement grows with an increase in temperature, but does not exceed 0.3-0.4%. It is possible that growth of the decrement depends on an increase in the forces of friction acting on the oscillating dislocation [2].

For the aluminum alloys AK4-1 (Fig. 2e) and VD-17 (Fig. 2d), studied during bending oscillations, the following characteristics were noted: first, high values and amplitude dependence of the decrement and, second, a significant growth of the decrement with an increase in temperature. At the same time tests with the



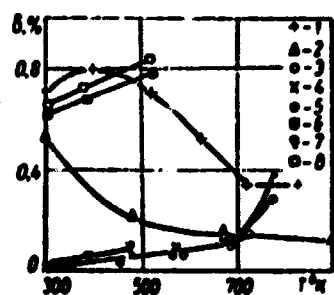


Fig. 4. Temperature dependence of decrements in compressor materials at the level of maximum dynamic stresses, $\sigma = 0.2 \sigma_{-1}$:

1 - steel EI961;
2 - steel EI696M;
3 - titanium alloy VTZ-1; 4, 5 - titanium alloy VT-8 (annealed and tempered, respectively); 6 - aluminum alloy AK4-1;
7, 8 - aluminum alloy VD-17 (tension-compression and bending, respectively).

specimens subjected to longitudinal oscillations (Fig. 3) did not reveal a significant dependence of the decrement on either oscillation amplitude or temperature. However, the decrement values were an order of magnitude smaller than those obtained during the investigation of bending oscillation; this is explained by the different role played during the indicated types of testing by the surface layer of the specimens, which has been strongly injured by mechanical treatment.

Figure 4 shows the temperature dependence of the decrement for the considered materials during dynamic stresses comprising 0.2 of the endurance limit. As is evident, at temperatures up to 670°K the damping properties of steel EI961 are an order of magnitude higher than those of the titanium alloys, although with an increase in temperature the difference is reduced and at 770°K the values of the decrement are virtually identical for steel EI961 and the alloy VT-8. For steel EI696M the decrement drops sharply with an increase in temperature and at 770°K is approximately 2-3 times less than that for the alloy VT-8.

Under conditions of bending oscillations of the specimens in the temperature range 300-520°K the logarithmic decrement for the aluminum alloys has approximately the same values as for steel EI961, while during longitudinal oscillations the values are closer to those for the titanium alloys. In connection with the

mechanical treatment of the large number of defects in the surface layers of the aluminum specimens, in the future we will evaluate the vibration strength of aluminum alloys on the basis of data obtained during longitudinal oscillations.

Analysis of the damping properties of materials does not give a total evaluation of their vibration strength. High vibration strength of a material is determined by an optimum combination of fatigue and damping properties, which will ensure reliable operation of a part under the maximum permissible dynamic stresses; therefore evaluation of the vibration strength of a material can be based on calculation of the criterion of vibration strength, $R = (\sigma_{-1}/k)\delta^*$, where σ_{-1} is the endurance limit of the material, k is the safety factor which determines the level of permissible dynamic stresses in the part, and δ^* is the logarithmic decrement for the material during the stress σ_{-1}/k .

During calculation of the vibration strength criterion it is difficult to select a numerical value for the safety factor k , which depends on the properties of the material and the operating conditions. This stems from the fact that the selection can be made only for each specific case. Therefore the vibration strength criterion of a material should be calculated for the entire range of possible values of the safety factor k ; the latter can be obtained on the basis of analyzing the dependence of the quantity $\sigma\delta$ on the ratio σ/σ_{-1} (δ is the logarithmic decrement at stress σ).

Curves of the quantity $\sigma\delta = f(\sigma/\sigma_{-1})$, constructed on the basis of ordinary experimental dependences of the decrement on stress amplitude, will give a set of vibration strength criteria at different values of permissible dynamic stresses and will make it possible to compare different materials at identical and different values of the safety factor k .

The functions $\sigma\delta = f(\sigma/\sigma_{-1})$ for room and maximum operating temperatures were constructed for each material on the basis of

obtained experimental results with respect to damping capability and endurance limit (Fig. 5).

From the relationships given it is evident that steel EI961 has the greatest vibration strength at room temperature; it exceeds that of titanium and aluminum alloys by 10-25 times at all levels of dynamic stresses. Up to a stress level on the order of $0.2\sigma_{-1}$ steel EI696M has approximately the same vibration strength as steel EI961, but at higher stress levels its vibration strength is 1.5-2 times lower. With an increase in temperature the vibration strength of the steels EI961 and EI696M is reduced owing to a drop in both fatigue and damping properties; at maximum operating temperatures (823°K for EI961 and 873°K for EI696M) it is reduced by 3-5 times.

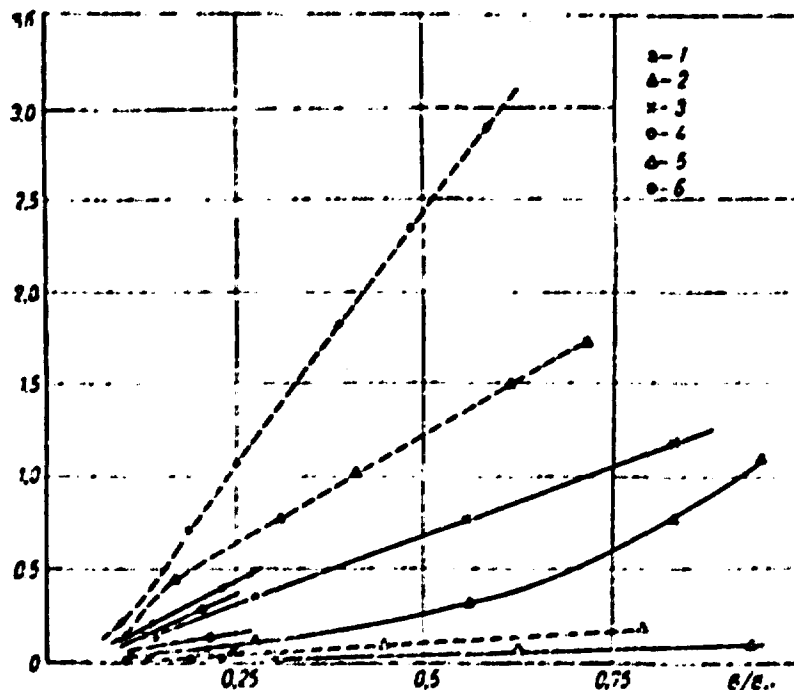


Fig. 5. Vibration strength of compressor materials at 293°K (broken lines) and at maximum operating temperature for the material (solid lines):
 1 - steel EI961 (823°K); 2 - steel EI696M (873°K); 3 - titanium alloy VT-2 (annealing, 773°K); 4 - titanium alloy VTZ-1 (723°K); 5 - aluminum alloy VD-17 (523°K); 6 - titanium alloy VT-8 (tempering, 773°K).

The vibration strength for the titanium alloys is greater at the maximum working temperatures (VTZ-1, 723°K; VT-8, 773°K) than at room temperature, since at these temperatures there is a sharp (several times) growth in the logarithmic decrement, while the endurance limit drops insignificantly (by no more than 20-25%). The vibration strength of steel EI696M (at 873°K) is approximately 1.5-2.5 times less than that of steel EI961 (at 823°K), while that for the alloy VD-17 (523°K) is 15-20 times less.

During comparison of materials in aeronautical engineering, when design weight plays an important role, the characteristic of specific strength is introduced — i.e., the ratio of strength to density of the material. Therefore it will obviously be useful to introduce the concept of the criterion of specific vibration strength of the material, which can be evaluated by analyzing the relationship $\sigma\delta/\rho = f(\sigma/\sigma_{-1})$, where ρ is the density of the material.

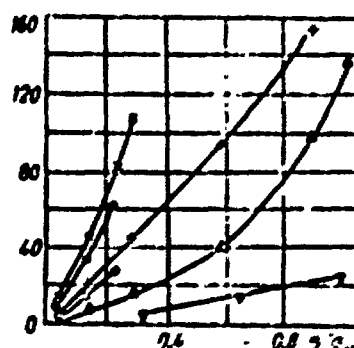
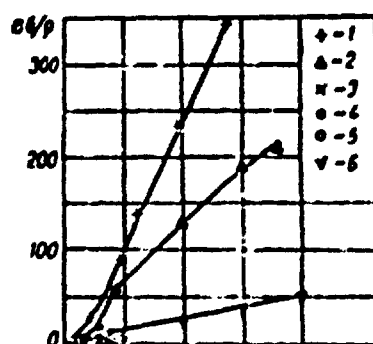


Fig. 6. Specific vibration strength of certain compressor materials as a function of the level of dynamic stresses:

a — at 293°K; b — at maximum temperature.
 1 — Steel EI961 (823°K);
 2 — steel EI696M (873°K);
 3 — titanium alloy VT-8 (annealing, 773°K);
 4 — titanium alloy VT-8 (tempering, 773°K);
 5 — titanium alloy VTZ-1 (723°K); 6 — aluminum alloy VD-17 (523°K).

Figure 6 shows the graphs of this relationship at room and maximum operating temperature for each material. From the figure it is evident that at room temperature (293°K, Fig. 6a) the specific vibration strength of steel EI961 is 5-10 times higher than that of the titanium and aluminum alloys, while at the maximum operating temperature of the material (Fig. 6b) it is 6-8 times higher than the alloy VD-17 and approximately the same as that for alloy VTZ-1, but at the same time two times lower than alloy VT-8. The fact that the vibration strength value is lower for alloy VTZ-1 than for VT-8 can apparently be explained by the difference in structure of the tested specimens.

Thus, it is possible to conclude that among all the materials considered the alloy VT-8 possesses the best characteristic of vibration strength for operation at high temperatures.

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