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# CREEP FAILURE TIME OF THIN-WALLED PIPES UNDER COMBINED TORSION, BENDING AND TENSION

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## ABSTRACT

The creep failure time is calculated for rectilinear thin-walled pipes subjected to torsion as well as tension and bending. The calculating of the failure time is given using the concept of equivalents stresses. The equivalent stresses are found from the mixed delayed-failure criterion relating the maximum normal stress and the intensity of tangent stresses. Results for failure time which are made of steel alloys are presented and compared with the results obtained by Golub et al. (2004) [3]. The present work can be used to calculate the time to creep failure for any thin-walled pipes under torsion, axial load and bending.

تم حساب زمن الإنهيار الزحفي لمواسير رقيقة الجدار (مستقيمة الخطوط) تحت تأثير اللي وكذلك كلا من الثني و الشد. و قد تم حساب هذا الزمن باستخدام مبدأ الإجهادات المكافئة. و هذه الإجهادات المكافئة تم ايجادها من نظرية الإنهيار المتأخر المختلطة لأقصى إجهاد شد ولكثافة الإجهادات المماسية. يتتضمن البحث نتائج لزمن الإنهيار لسبائك من الصلب و قد قورنت هذه النتائج مع نتائج (جولب ٢٠٠٤) للمواسير. هذا البحث يمكن استخدامه لحساب زمن الإنهيار الزحفي لأي مواسير رقيقة الجدار تحت تأثير اللي أو الشد أو الثني أو جميعهم معاً.

***Keywords***: creep failure, plane bending, thin-walled pipe, torsion, uniaxial tension

## 1. INTRODUCTION

Elements of steam and gas turbines, jet engines, steam boilers, rockets, oil and gas processing plants are widely used of thin-walled pipes, which are fall into the category of structural elements that should be subjected to creep analysis. The basis of the creep analysis is the time to failure calculated for thin-walled pipe under different loading conditions. Altenbach [1] has introduced a review to topical problems and applications of creep theory. El Megharbel [2], Golub [3] and Golub [4] have calculated the failure time for thin walled pipes under internal pressure as well as for polymeric tubes. The time to failure for thin-walled pipes under pure torsion, under torsion and tension, and under torsion and internal pressure have derived based on the generalized mixed failure criterion [3].

A creep theory with anisotropic hardening is proposed by Zolochevsky [5] for initially isotropic materials with different properties in tension and compression. All the material parameters in the creep theory have been obtained from a series of uniaxial tension tests, uniaxial compression tests and pure torsion tests with constant stresses.

The up-to-date engineering applications require that new adequate mathematical models for material deformation as well as structural analysis method should be developed. Sklepus [6] has discussed the creep of plates that undergo damage due to in-plane mechanical loads using a method for solving the initial boundary value problem. Whereas, Kovrizhnykh [7] has introduced an ideal-creep model, using the Coulomb–Mohr criterion for considering the long-term strength of metals and the ultimate state. In addition Kovrizhnykh [8] have discussed the creep equations and the long-term strength criterion for plane stress using the same criterion.

Golub [9] have evaluated the fatigue strength of materials and structural members under high-cycle loading with repeated stress cycle, using well-known empirical relations between static and cyclic limiting stresses. While Golub [10] has studied the experimental analysis of high-temperature creep, fatigue, and damage.

Tinga [11] are proposed a damage model for single crystal Ni-base superalloys that integrates time-dependent and cyclic damage into a generally applicable time-incremental damage rule. Yang [12] are proposed a simple stress controlled fatigue-creep damage evolution model, based on the ductility dissipation theory and effective stress concept of continuum damage mechanism, and damage constants can be obtained through fatigue-creep tests directly.

Galishin [13] has developed a procedure for determining the parameters of creep and creep-rupture strength that appear in constitutive equations of thermoviscoplasticity for describing nonisothermal processes of deformation and damage accumulation in isotropic materials due to creep.

A power-law creep constitutive model was developed by Kim [14] to describe the densification behavior of powder compacts during pressure-assisted compaction at elevated.

The equivalent-stress methods of long-term strength analysis of pipes are the most efficient and widely used in current design practice. The accuracy of calculations strongly depends on the adequacy of the equivalent stresses to the stress and failure modes of the pipe and on the degree of agreement between the material constants and long-term strength characteristics obtained under uniaxial tension.

## 2. ANALYSIS

This paper is interested in thin-walled pipe under torsion as well as axial load and bending.

### 2.1 THE FAILURE OF THIN-WALLED PIPES UNDER TORSION [3]

### 2.1 1 FAILURE UNDER TORSION

Golub [3] have derived a formula to evaluate the creep time ($t_{RT}$) for pipes under torque $M_T$ only, where the stress state is:

$$\sigma_1 = \frac{2M_T}{\pi D_m^2 h} = \tau, \quad \sigma_2 = 0, \quad \sigma_3 = -\frac{2M_T}{\pi D_m^2 h} = -\tau \qquad (1)$$

and

$$t_{RT} = \frac{1}{B\left[\dfrac{\sqrt{6} + \left(6 - \sqrt{6}\right)\beta}{3}\right]^m \tau^m} \qquad (2)$$

Where $D_m$ is the diameter of the median surface and h is the wall thickness,

The material constant β is

$$\beta = \frac{2\left(3\sigma_t - \sqrt{6}\tau_t\right)}{\left(6 - \sqrt{6}\right)\sigma_t} \qquad (3)$$

### 2.1.2 FAILURE UNDER TORSION AND AXIAL LOAD

For a rectilinear thin-walled pipe under a torque MT and an axial tensile load N, the equilibrium conditions for the pipe yield

$$\sigma_1 = \frac{1}{2}\left[\frac{N}{\pi D_m h} + \sqrt{\left(\frac{N}{\pi D_m h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

$$\sigma_2 = 0 \qquad (4)$$

$$\sigma_3 = \frac{1}{2}\left[\frac{N}{\pi D_m h} - \sqrt{\left(\frac{N}{\pi D_m h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

And the creep time is given as

$$t_{RT} = \frac{1}{B}\left[\frac{2\sqrt{3+\nu^2} + \left(3\sqrt{4+\nu^2} - \sqrt{2\left(3+4\nu^2\right)}\right)\beta}{3}\right]^{-m} \tau^{-m} \qquad (5)$$

Where,

$$\sigma_n = \frac{N}{\pi D_m h}, \quad \tau = \frac{2M_T}{\pi D_m^2 h}, \quad \nu = \frac{\sigma_n}{\tau} \qquad (7)$$

### 2.2. FORMULATION OF THE PROBLEM AND THE INITIAL RELATIONS (THE PRESENT WORK)

Consider a long rectilinear thin-walled pipe of circular cross section under creep conditions. Denote the diameter of the median surface by $D_m$ and wall thickness, which is constant, by h. It is assumed that $2h \ll D_m$.

The pipe is subjected to torque $M_T$ in combination with axial tensile force N and bending moment $M_B$. Under creep, the external load remains constant. The ends of the pipe are not restrained, and its deformation is free. The material of the pipe is homogeneous, isotropic, and incompressible, and its initial state is elastic. The time to failure $t_{RT}$ of the pipe is found using the approach Golub [3] based on the concept of equivalent stress as some scalar characteristic of the initial stress of the pipe. The equivalent stress relates the failure of the pipe under arbitrary stress and the failure of a cylindrical specimen under uniaxial tension. Therefore,

$$t_R = \frac{1}{B(\sigma_t)^m} \Rightarrow t_{RT} = \frac{1}{B(\sigma_{eqv})^m} \qquad (8)$$

Where $t_R$ and $\sigma_t$ are the time to failure and failure stress of smooth cylindrical specimens under uniaxial tension; $\sigma_{eqv}$ is the equivalent stress; B and m are material constants determined from standard uniaxial-tension creep-rupture tests on smooth cylindrical specimens. In what follows, we consider that for the values of B and m found, the delayed-failure patterns of smooth specimens and thin-walled pipes are identical. If the standard long-term strength curve has breaks, then the values of B and m are calculated for each section of the curve.

The combination of torsion, tension, and bending induces plane stress in thin-walled pipes. A mixed delayed-failure criterion in the form Golub [15] is

$$\sigma_{eqv} = \begin{cases} \alpha\sigma_{max} + (1-\alpha)s_i & \text{for } \sigma_1 > \sigma_2 > 0, \quad \sigma_3 = 0 \\ 2\beta\tau_{max} + (1-\beta)\tau_{oct} & \text{for } \sigma_1 > 0, \sigma_2 = 0, \quad \sigma_3 < 0 \end{cases} \qquad (9)$$

can be used as equivalent stress $\sigma_{eqv}$. This criterion accounts for the signs of the principal stresses and relates the maximum normal stress $\sigma_{max}$,

$$\sigma_{max} = \sigma_1 \qquad (10)$$

the intensity of tangential stresses,

$$s_i = \frac{1}{\sqrt{3}}\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \qquad (11)$$

the double maximum tangential stress $2\tau_{max}$,

$$2\tau_{max} = \sigma_1 - \sigma_2 \qquad (12)$$

and the octahedral tangential stress $\tau_{oct}$,

$$\tau_{oct} = \frac{\sqrt{2}}{3}\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \qquad (13)$$

where $\sigma_1$ and $\sigma_2$ are the principal normal stresses ($\sigma_1 > \sigma_2$); and $\alpha$ and $\beta$ are experimentally determined material constants reflecting the effect of the mode of plane stress ($\sigma_2$ is any nonzero second principal stress). When thin-walled pipes are subjected to torsion in combination with both tension and bending, the signs of the principal stresses coincide. Substituting the first relation in (9) into Eq. (8) and taking (10) and (11) into account, we obtain an equation for the time to failure in terms of principal stresses

$$t_{RT} = \frac{1}{B\left[\frac{\sqrt{3}\alpha\sigma_1 + (1-\alpha)\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}}{\sqrt{3}}\right]^m} \qquad (14)$$

which in fact determines the time of occurrence of local failure.

Substituting the second relation in (9) into (8) and taking (12) and (13) into account, we obtain an equation for the time to failure when the signs of the principal stresses are opposite:

$$t_{RT} = \frac{1}{B\left[\frac{3\beta(\sigma_1 - \sigma_2) + (1-\beta)\sqrt{2(\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2)}}{\sqrt{3}}\right]^m} \qquad (15)$$

These times in fact specify the moments of occurrence of local failure.

### 2.2.1 FAILURE UNDER TORSION AND BENDING

Consider a rectilinear thin-walled pipe with end plates under torque $M_T$ and bending moment $M_B$. We assume that the pipe is long. The plane stress state in the median surface of the pipe is membrane and statically determinate. The equilibrium conditions yield

$$\sigma_1 = \frac{1}{2}\left[\frac{2M_B}{\pi D_m^2 h} + \sqrt{\left(\frac{2M_B}{\pi D_m^2 h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

$$\sigma_2 = 0 \qquad (16)$$

$$\sigma_3 = \frac{1}{2}\left[\frac{2M_B}{\pi D_m^2 h} - \sqrt{\left(\frac{2M_B}{\pi D_m^2 h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

Taking the following notation,

$$\sigma_b = \frac{2M_B}{\pi D_m^2 h}; \qquad \tau = \frac{2M_T}{\pi D_m^2 h}; \qquad \mu = \frac{\sigma_b}{\tau} \qquad (17)$$

$\sigma_b$ and $\tau$ are the bending and torsional stresses, and $\mu$ is the dimensionless parameter, a measure of variation in stress state of the thin-walled pipe under torque.

Substituting Eq. (16) into Eq. (15) yields the time to failure.

$$t_{RT} = \frac{1}{B}\left[\frac{\left(3\sqrt{4+\mu^2}\right)\beta + \sqrt{2(3+\mu^2)}(1-\beta)}{6}\right]^{-m}\left(\frac{2M_T}{\pi D_m^2 h}\right)^{-m} \qquad (18)$$

or;

$$t_{RT} = \frac{1}{B}\left[\frac{2\sqrt{3+\mu^2} + \left(3\sqrt{4+\mu^2} - \sqrt{2(3+4\mu^2)}\right)\beta}{3}\right]^{-m}\tau^{-m} \qquad (19)$$

And the material constant $\beta$ can be determined from the relation in [15] as

$$\beta = \frac{\sqrt{4+\mu^2}\left(3\sigma_t - \sqrt{2(3+\mu^2)}\tau_t\right)}{\left(3\sqrt{4+\mu^2} - \sqrt{2(3+\mu^2)}\right)\sigma_t} \qquad (20)$$

where $\tau_T$ and $\sigma_t$ are the experimentally determined average (in view of the statistical properties of the materials) long-term strengths, at the same time to failure, for a thin-walled tubular specimen under torsion and tension. Eqs. (19) and (20) are identical to Eqs. (5) and (6), *instead of* ($\mu$) *the parameter* ($\nu$) is appeared.

### 2.2.2 FAILURE UNDER TORSION, TENSION AND BENDING

Consider a rectilinear thin-walled pipe with end plates under a torque $M_T$ and both axial load N and bending moment $M_B$. We assume that the pipe is long. The plane stress state in the median surface of the pipe is membrane and statically determinate. The equilibrium conditions yield

$$\sigma_1 = \frac{1}{2}\left[\left(\frac{N}{\pi D_m h} + \frac{2M_B}{\pi D_m^2 h}\right) + \sqrt{\left(\frac{N}{\pi D_m h} + \frac{2M_B}{\pi D_m^2 h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

$$\sigma_2 = 0 \qquad (21)$$

$$\sigma_3 = \frac{1}{2}\left[\left(\frac{N}{\pi D_m h} + \frac{2M_B}{\pi D_m^2 h}\right) - \sqrt{\left(\frac{N}{\pi D_m h} + \frac{2M_B}{\pi D_m^2 h}\right)^2 + 4\left(\frac{2M_T}{\pi D_m^2 h}\right)^2}\right]$$

Substituting Eq. (21) into Eq. (15) (taking in consideration that $\sigma_2$ in Eq. (15) is any nonzero second principal stress). Yields the time to failure as;

$$t_{RT} = \frac{1}{B}\left[\frac{\left(3\sqrt{(\nu+\mu)^2+4}\right)\beta + \left(\sqrt{2(\nu+\mu)^2+6}\right)(1-\beta)}{3}\right]^{-m}\left(\frac{2M_T}{\pi D_m^2 h}\right)^{-m} \qquad (22)$$

or

$$t_{RT} = \frac{1}{B}\left[\frac{\left(\sqrt{2(\nu+\mu)^2+6}\right) + \left(3\sqrt{(\nu+\mu)^2+4} - \sqrt{2(\nu+\mu)^2+6}\right)\beta}{3}\right]^{-m}\tau^{-m} \qquad (23)$$

Where ν and μ are the dimensionless parameter, a measure of variation in stress state of the thin-walled pipe under torque, according to $\sigma_t$, $\sigma_b$ and $\tau$, the tensile, bending and torsional stresses respectively (Eqs. 7 and 17).

The material constant β is determined from [15] as:

$$\beta = \frac{\left(\sqrt{(\nu+\mu)^2+4}\right)\left(3\sigma_t - \left(\sqrt{2(\nu+\mu)^2+6}\right)\tau_t\right)}{\left(3\sqrt{(\nu+\mu)^2+4} - \sqrt{2(\nu+\mu)^2+6}\right)\sigma_t} \qquad (24)$$

where $\tau_T$ and $\sigma_t$ are the experimentally determined average (in view of the statistical properties of the materials) long-term strengths, at the same time to failure, for a thin-walled tubular specimen under torsion and tension. The other notation coincides with that adopted in (7), (17), (21) and (23).

Substitute in Eqs. (23) and (24) with ν=0 and μ= 0 (i.e. pipe is under torsion only) yields to the same eqs. (2) and (3) respectively. Substitute in Eqs. (23) and (24) with ν=0 yields the same Eqs.(19) and (20) respectively. Otherwise substitute in Eqs. (23) and (24) with μ=0 yields the same Eqs.(5) and (6) respectively (i. e. the same work of Golub [3]).

## 3. RESULTS AND DISCUSSION

The time to creep failure of thin-walled pipes under torsion combined with both axial load and bending is introduced in the previous section. These analytical are concerned with long rectilinear thin-walled pipe in order to predict the time failure of the pipe according to the parameters of the stress state as well as the torsion of the pipe. The used materials properties are shown in Table 1.

The creep failure time for the different materials (Table 1) versus torsion is shown in Fig. 1, after using Eqs. (2 and 3). The Alloy É1437B at 600 °C gives much higher failure time compared by the other materials, for the same torsion value, which is almost 38 times for Alloy É1437B at 700 °C, 24.5 x $10^2$ times for Alloy É1437B and 23.5x $10^7$ times for Steel 1Kh13N16B. The reason for such behavior is that the material has the lowest value of material constant (B) compared by the other materials (see Table 1).

The creep failure time for the different materials (Table 1) versus torsion is also studied for stress state torsion and tension (i.e. Eqs. (5 and 6)), Fig. 2. The failure time for Steel 1Kh13N16B is much lower than the failure time for the other materials, is almost 5x$10^{-9}$ times the value of the failure time for Alloy É1437B at 600 °C. This behavior is due to the lowest value of constant B for Steel 1Kh13N16B.

Fig. 3 shows the results obtained for the failure time versus the torsion for pipes under torsion and bending (Eqs. 19 and 20). The Alloy É1437B at 600 °C has the highest failure time; as expected; compared by the other materials.

The failure time as a function of torsion (τ) for pipes under torsion as well as tension and bending is shown in Fig. 4. The results obtained from Eqs. (23 and 24) for materials in Table 1. The failure time is much higher for Alloy É1437B at 600 °C compared with the other materials for the same amount of torsion. This was expected but which is not expected is the value of such higher amount, is almost 2.5 times for alloy É1437B at 700 °C. This reason for such behavior is that the amount of tension and bending parameters (ν and μ) for both materials is almost closed.

The results demonstrate similar general trends between Figs 1-4, except that the values are different due to the difference in stress state. Figs. 5-8 show the failure time as a function of torsion (τ) for different stress state, separately as specific material (Table 1). The failure time for alloy É1698VD is shown in Fig. 5 for pure torsion, torsion and tension, torsion and bending; and torsion as well as tension and bending. The failure time decreased as pipes stressed by tension, bending or bending with tension; besides to the torsion (τ). Fig. 6 gives the failure time as a function of torsion (τ) for steel 1Kh13N16B under pure torsion, tension and torsion, bending and torsion as well as tension, bending and torsion. It is worth mentioning that, in increase of torsion with constant of ν or μ, is required increasing in tension load or in bending moment respectively (see Eqs. 7 and 17). This resulted a low failure time with increasing torsion, especially, when the pipes stressed with torsion as well as tension and bending. The failure time versus torsion for alloy É1437B at 600 °C and at 700 °C is shown in Figs. 7 and 8 respectively. The failure time reached very low values as the applied torsion increased to about 9 MPa and 10 MPa for alloy É1437B at 600 °C and at 700 °C, respectively. The failure time for pipes under torsion as well as tension and bending is much lower than the failure time for pipes under only torsion; which is almost 0.6 times , 0.05 times, 0.04 times and 0.55 times the failure time of pipes under torsion for alloy É1698VD, steel 1Kh13N16B and alloy É1437B (600 °C - 700 °C) respectively (see Figs. 5-8).

Moreover, the results demonstrate similar general trends between Figs. 5-8, except that the values are different due to the difference in stress state.

## 4. CONCLUSION

The time to failure for thin-walled pipes under torsion as well as axial load and bending was calculated throughout the delayed-failure models. There are good agreements between the results of the present work in calculating the failure time and the results in Golub et al. [3]. This work presents mathematical models that can be used to calculate the failure time for any rectilinear thin-walled pipes under torsion as well as axial load and bending. Results for failure time of pipes which are made of different kind of steels are presented and compared with the results which are calculated using the analysis of Golub [3]. In this paper, the equivalent stresses are used in the form of mixed delayed-failure criterion relating the maximum normal stress and the intensity of tangential stresses and containing one material constant. The failure criterion chosen has been tested for a plane stress state with principal stresses of opposite sign. The present work could be applied to any material and any thin-walled tube with different dimensions which makes the analysis a basic step for computer aided creep failure.

## 5. REFERENCES

[1] H. Altenbach, "Topical problems and applications of creep theory" Int. Appl. Mech. 39, No. 6, 631-655 (2003).

[2] A. El Megharbel, "Creep Failure time of thin-walled pipes under combined internal pressure, bending and tension", ERJ Faculty of Engineering Minoufiya University, Vol. 32, No. 3, pp. 359-366 (2009).

[3] V. P. Golub, V. V., Kasperskaya, A. A., Rusinov, "Time to creep failure of thin-walled cylindrical pipes under torsion", Int. Appl. Mech. 40, No. 6, 686–693 (2004).

[4] V. P. Golub, Yu. M., Kobzar, A. A., Rusinov, "Calculation of the long-term strength on thin-walled polymeric tubes under biaxial loading", Mechanics of Composite Materials, Vol. 40, No. 6, 533-544 (2004).

[5] A. Zolochevsky, S. Sklepus, Yu. Kozmin, A. Kozmin, D. Zolochevsky, J. Betten, "Constitutive equations of creep under changing multiaxial stresses for materials with different behavior in tension and compression", Forsch Ingenieurwes 68, 182-196 (2004).

[6] S. N. Sklepus, "Plane stress creep of damaged plates, Strength of Materials", Vol. 39, No. 6, pp. 51 – 60 (2007).

[7] A. M. Kovrizhnykh, "On the long-term strength of metals and the ideal-creep model", Doklady physics, Vol. 52, No. 7, pp. 388-390 (2007).

[8] A. M. Kovrizhnykh, V. D. Baryshnikov, A. V. Manakov, A. F.Nikitenko, "Long-term strength of metals and creep equations based on the Coulomb-Mohr criterion", journal of Applied Mechanics and Technical Physics, Vol. 48, No. 6, pp. 871–877 (2007).

[9] V. P. Golub, A. D. Pogrebnyak, E. S. Kochetkova, "Fatigue strength of metals and composite under repeated high-cycle torsion", Int. Appl. Mech. 44, No. 2, 134-141 (2008).

[10] V. P. Golub, "Experimental analysis of high-temperature creep, fatigue, and damage. 2. basic laws", Int. Appl. Mech. 37, No. 5, 565-601 (2001).

[11] T. Tinga, W. A. M. Brekelmans, M. G. D. Geers, "Time-incremental creep–fatigue damage rule for single crystal Ni-base superalloys", Materials Science and Engineering A 508, 200–208 (2009).

[12] T. C. Yang, L. Chen, Z. C. Fan, X. D. Chen, J. L. Jiang, "A CDM-based study of fatigue-creep interaction behavior", International Journal of Pressure Vessels and Piping (under press).

[13] A. Z. Galishin, "Procedure of determining creep and creep-rupture strength parameters for isotropic materials under nonisothermal loading", Strength of Materials, Vol. 36, No. 4, 345-352 (2004).

[14] H. S. Kim, D. N. Lee, "Power-law creep model for densification of powder compacts", Materials Science and Engineering A271, 424–429 (1999).

[15] V. P. Golub, V. I. Krizhanovskii, A. A. Rusinov, "A mixed criterion of delayed creep failure under plane stress", Int. Appl. Mech. 39, No. 5, 556–565 (2003).

**Table 1.** The used materials [3]

| Material | °C | B, $MPa^{-m} h^{-1}$ | m | λ | ν(Eq.7) | μ(Eq.8) | β |
|---|---|---|---|---|---|---|---|
| Alloy É1698VD | 750 | $1.07.10^{-23}$ | 8.04 | 3.50 | 0.2 | 0.5 | 1.71 |
| Steel 1Kh13N16B | 700 | $1.08.10^{-13}$ | 4.95 | 3.9 | 1.3 | 1.6 | 1.82 |
| Alloy É1437B | 600 | $1.03.10^{-28}$ | 9.04 | 16.0 | 1.0 | 1.0 | 1.79 |
| | 700 | $9.44.10^{-28}$ | 9.43 | 29.5 | 0.3 | 0.4 | 1.71 |

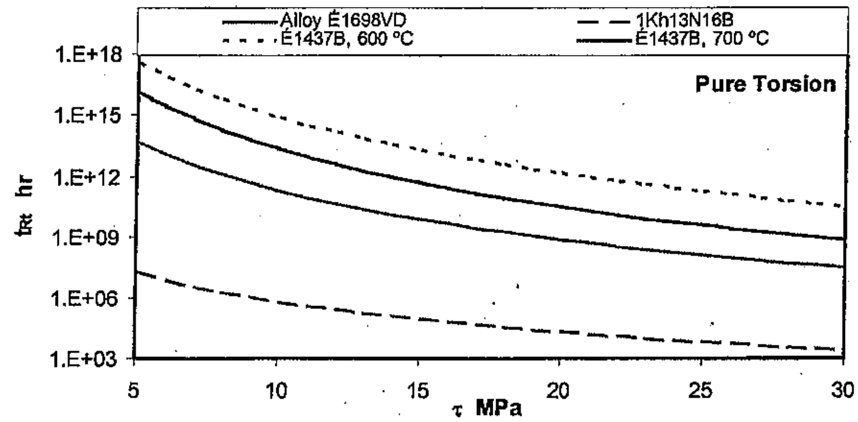


**Fig. 1** The relationship between the torsion and the failure time for Alloys shown in Table 1. (under pure torsion).

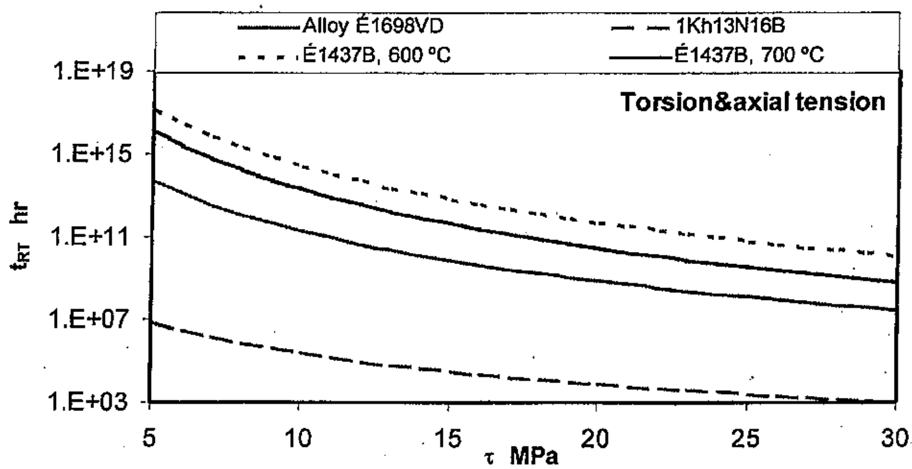


**Fig. 2** The relationship between the torsion and the failure time for Alloys shown in Table 1. (under torsion & axial tension).

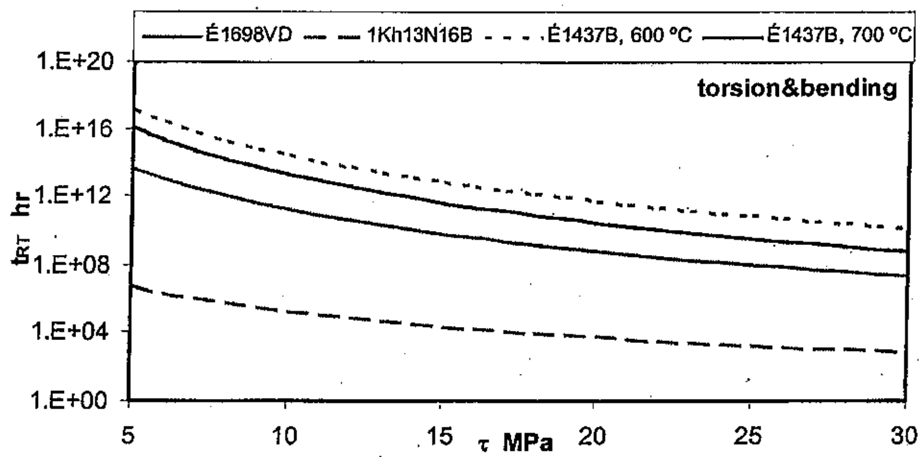


**Fig. 3** The relationship between the torsion and the failure time for Alloys shown in Table 1. (under torsion & bending).

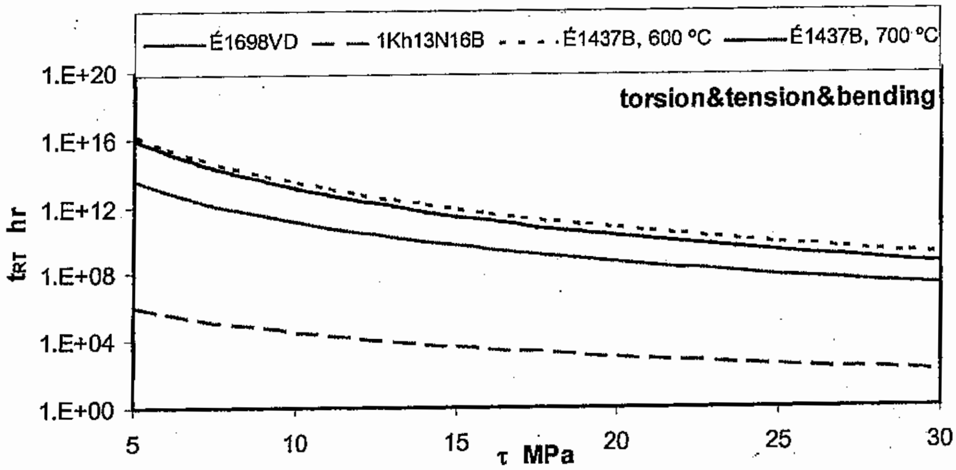


**Fig. 4** The relationship between the torsion and the failure time for Alloys shown in Table 1. (under torsion & tension & bending).

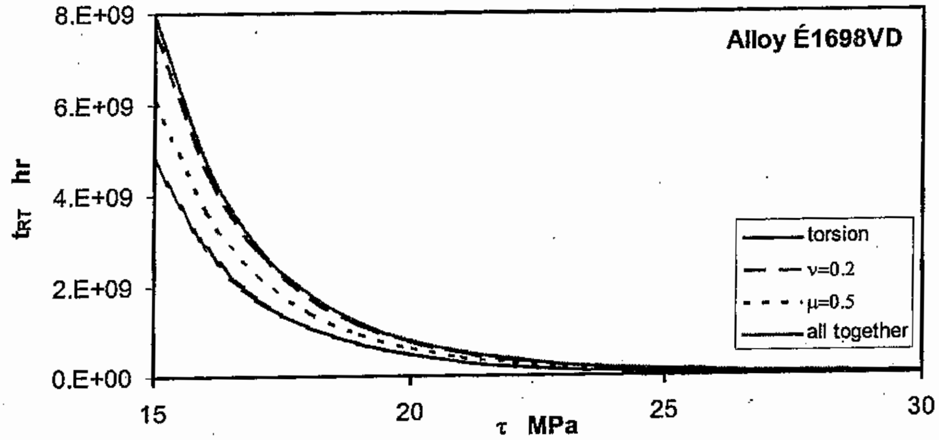


**Fig. 5** The relationship between the torsion and the failure time for Alloy É1698VD with ν and μ shown in Table 1.

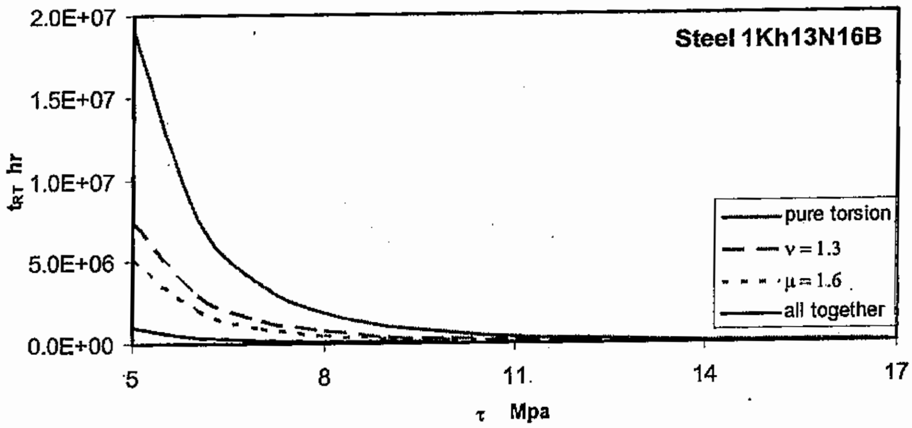


**Fig. 6** The relationship between the torsion and the failure time for Steel 1Kh13N16B with ν and μ shown in Table 1.

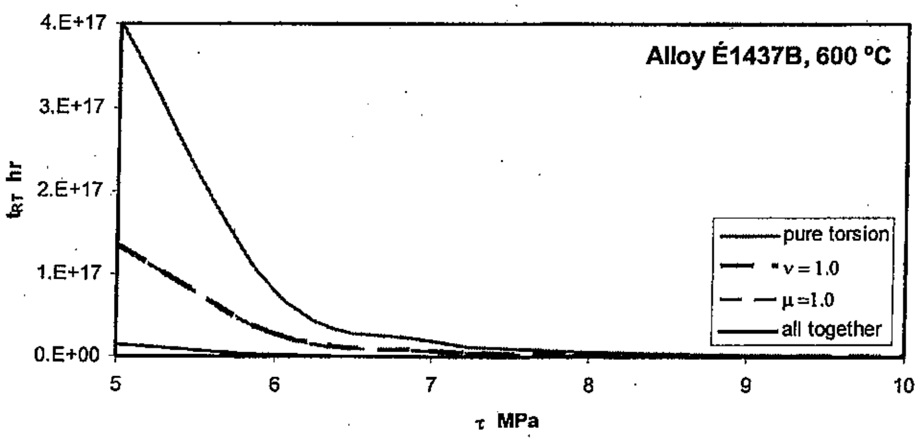


**Fig. 7** The relationship between the torsion and the failure time for Alloy É1437B with ν and μ shown in Table 1.

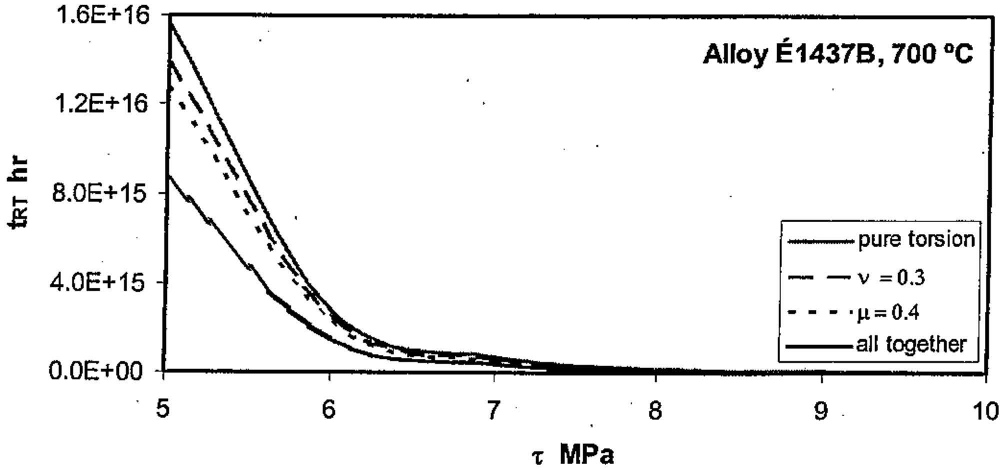


**Fig. 8** The relationship between the torsion and the failure time for Alloy É1437B with ν and μ shown in Table 1.