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EXPERIMENTAL VERIFICATION OF FAILURE CRITERION BASED ON SPECIFIC STRAIN WORK

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The difference between values of specific strain work needed for rupturing (at room temperature) the virgin specimen and that previously subjected to a loading process until the specified cycle number is reached had been proposed earlier by one of the authors as a material damage measure and failure criterion. These assumptions were verified during the investigation reported in this paper. The analysis of results obtained shows that the maximum of that difference is constant and independent of stress and temperature (for examined steels and process parameters applied); it can thus be accepted as a failure criterion.

1. Introduction

Prognosticating of the durability of structural components which operate in conditions of cyclic temperature and load variations calls for the acceptance of a failure criterion. As the basis of failure criteria one can assume the specific energy accumulated in a material during the loading process as a constant value for a given material, in other words, as a material constant.

Feltner and Morrow [1] assumed that the specific energy accumulated in a material during any loading process is equal to the specific energy needed for rupturing the specimen during the tensile test. Martin [2] and Romanov [3] found that only a part of energy accumulated in a unit volume of a material results in damage. Many failure criteria based on that concept were proposed but the main obstacle for a durability evaluation is that the loop-hysteresis shape and the appropriate part of energy stored in a unit material volume resulting in damage must be determined.

In the papers [4, 5] a new failure criterion was proposed, which allows us to avoid the difficulty mentioned above. The main ideas of that criterion are given below. Taking into consideration the results obtained by Feltner and Morrow [1], Martin [2] and Romanov [3], we can assume that the part of energy stored in a unit material volume during one cycle and resulting in damage depends on both the material and the parameters of the loading process but the total energy accumulated in a unit material volume during any loading process can be accepted as a material constant.

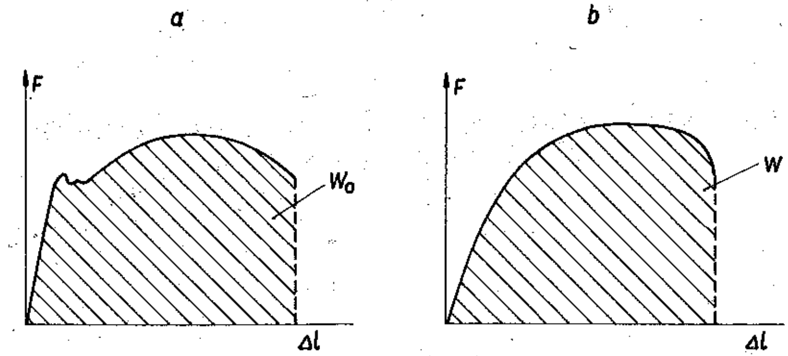

FIG. 1. Plots of force F against deformation Δl obtained during tensile test; a — for virgin specimen; b — for specimen which underwent thermal cycling until specified cycle number (without fracture).

It can be observed that strain work W measured during the tensile test at room temperature and needed for rupturing the specimen previously subjected to any loading process until a specified time or cycle number (without fracture) is smaller than strain work W_0 obtained for a virgin specimen, because of material damage accumulated during that previuos process (Fig. 1.).

The longer the loading time during the previous loading process, the greater the difference $(W_0 - W)$ between the strain work values obtained for the virgin and previously loaded specimen. To make the strain work values independent of the specimen volume, the specific strain work values W_s and W_{0s} must be introduced.

Assuming that proportionality exists between the energy accumulated in a unit volume of the specimen material resulting in damage and the difference $(W_{0s} - W_s)$ of the specific strain work obtained for the virgin and previously loaded specimen, that difference

$$W_{0s} - W_s = W_{NS} \tag{1}$$

can be accepted as a measure of material damage. The maximum W_{NS} value obtained for a specimen loaded until a cycle number close to fracture is reached should be a constant value and independent of the loading process parameters (stress and temperature). The maximum W_{NS} value (designated as $W_{NS\max}$) should be equal to specific strain work W_{0s} obtained for the virgin specimen. In consequence.

$$W_{NS\max} = \text{const} = W_{0s} \tag{2}$$

can be regarded as a failure criterion.

The aim of this research work was to verify that failure criterion

2. Experimental results

The investigation program included the checking of both the initial stress change effect at a constant shape of the thermal cycle and the effect of maximum temperature changes at a constant initial stress. The minimum temperature of the cycle was constant and equal to 573 K for all examined specimens.

Solid specimens made of two types of heat-resistant steels (H23N18, 50H17617) were used in the investigation. The designation of steels are in accordance with Polish Standards. The specimens were fixed at the upper ends using an articulated joint and loaded with static loads at the lower ends. They were heated by an electric current (resistance method) up to the maximum temperature and then cooled with air to the minimum temperature. Different saw-shaped cycles of constant heating speed (10 K/s) were used. Parameters of the loading process are presented in Table 1. Temperature

Table 1. Dependence of coefficients *a* and *b* cycle number to fracture and maximum values of material damage degree (minimum temperature of cycle 573 K).

Steel type	Maximum temperature of cycle [K]	Initial stress [MPa]	Coefficient values with 95% confidence range [J/cm³]		Maximum values of material damage degree: Calculated from equation (3) $\frac{W_{Nfs\max}}{\bar{W}_{0s}}$
			a	*b*	
H23N18	973	176.5	24±30	0.29±0.08	0.86
	1023	176.5	33±15	1.9 ±0.2	0.85
	1073	176.5	21±16	11.3 ±1.4	0.95
	1073	98.0	14±36	0.58±0.16	0.79
	1173	98.0	36±34	8.3 ±3.1	0.80
	1173	63.5	17±26	1.7 ±0.4	0.88
50H17G17	923	372.5	146±31	4.0 ±1.7	0.87
	923	333.5	121±28	1.25±0.55	0.82
	923	294.0	114±15	0.44±0.10	0.81
	923	255.0	121±36	0.18±0.09	0.92

variations were measured using the PtRh-Pt thermocouple. Length variations were measured using an inductive displacement gauge and recorded as a function of time and cycle number.

2.1. Specific strain work evaluation

One series of specimens was subjected to the loading process until fracture was reached while for the second series the loading process was stopped after a specified cycle number; the volumes of these specimens were

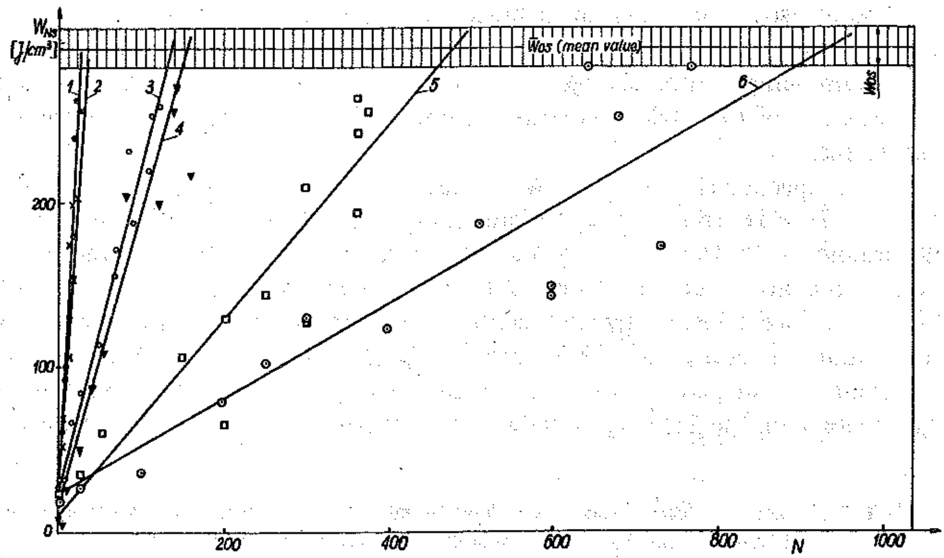

FIG. 2. Specific strain work W_{NS} dependence on cycle number N for H23N18 steel; *1* — 176.5 MPa, 573–1073 K; *2* — 98 MPa, 573–1173 K; *3* — 176.5 MPa, 573–1023 K; *4* — 63.5 MPa, 573–1173 K; *5* — 98 MPa, 573–1073 K; *6* — 176.5 MPa, 573–973 K.

then evaluated. The specimens subjected to a specified cycle number were broken in tension at room temperature using the Instron machine supplied with an integrator, and strain work W was measured for each specimen. Virgin specimens were also broken in tension for strain work W_0 evaluation. The specific strain work values W_s and W_{0s} were then calculated. The mean values of W_{0s} were found for the examined steels, and W_{NS} values were then obtained from Eq. (1). The W_{NS} values obtained for each specimen previously subjected to the loading process until a specified cycle number was reached are shown in Figs. 2 and 3. The 95% confidence intervals of mean values of W_{0s} are also shown in Figs. 2 and 3.

2.2. Analysis of stress and temperature influence

Analysis of the results given in Figs. 2 and 3 shows that the W_{NS} value depends on the cycle number and on the parameters of the loading process.

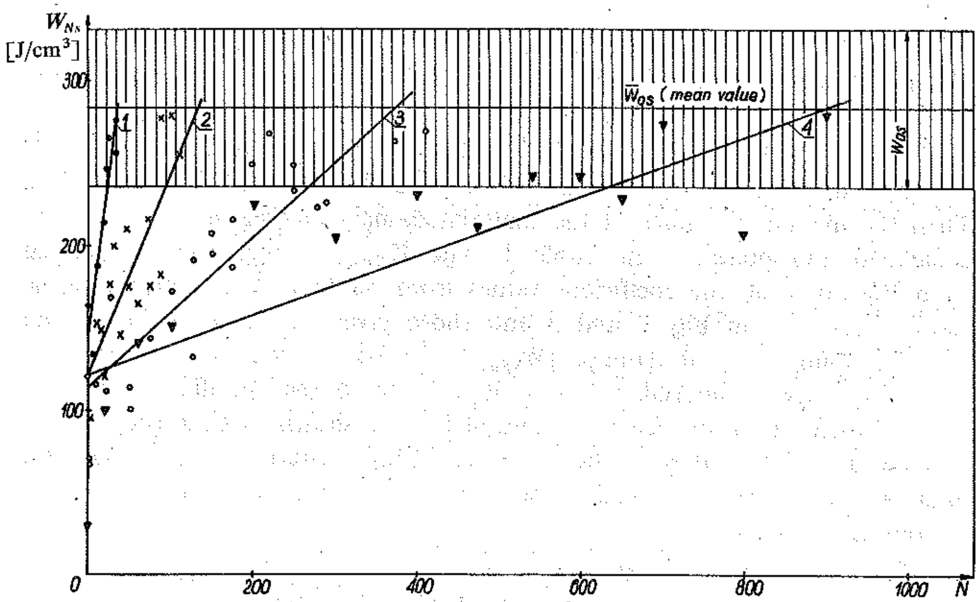

FIG. 3. Specific strain work W_{NS} dependence on cycle number N for 50H17G17 steel; *1* — 372.5 MPa; *2* — 333.5 MPa; *3* — 294 MPa; *4* — 255 MPa.

The linear correlation between W_{NS} and the cycle number N can be used with the probability equal to 0.999 for all applied loading process parameters for both steels examined. The dependence of W_{NS} on N is of the form

$$W_{NS} = a + bN, \tag{3}$$

where the a and b — coefficients are dependent on both the material type and cycle number to fracture. The values of the coefficients a and b (with 95% confidence intervals) are presented in Table 1. Analysis of the results presented in Table 1 shown that the value of a depends on the steel type only but the value of b depends for a given material on the cycle number to fracture, in other words, on stress and temperature. Analysis of the changes of the coefficient b value as a function of initial stress at a constant temperature range performed for 50H17G17 steel shows that b is an exponential function of initial stress. A similar analysis performed for specimens made of H23N18 steel examined at constant force resulting in tensile stress of 176.5 MPa shows that b is also an exponential function of maximum temperature.

As can be seen in Figs. 2 and 3 the W_{NS} value depends for a given material on the cycle number to fracture N_f. Maximum values of W_{NS}, however, are independent of the N_f value, in other words, on initial stress and maximum temperature. The $W_{NS\max}$ values are close to the specific strain work W_{0s} obtained for virgin specimens.

To make a comparison of the results obtained for different materials possible, the relative value of material damage W_{NS}/W_{0s} was introduced [4]. Then the maximum values of the material damage degree $W_{Nfs\max}/W_{0s}$ were calculated and presented in Table 1. The $W_{Nfs\max}$ values were calculated from Eq. (3) using the coefficient values from Table 1. The analysis of the results presented in Fig. 2 and 3 and those given in Table 1 shows that the maximum value of damage ($W_{NS\max}$) can be considered as a constant value for a given material, and that it is close to the specific strain work W_{0s} obtained for virgin specimens. Thus Eq. (2) is shown to be approximately fulfilled, and the validity of the proposed failure criterion is confirmed for uniaxial stress and examined steels, as well as for the loading process parameters applied.

The $W_{NS\max}$ values obtained for specimens made of H23N18 steel are slightly lower than those obtained for specimens made of 50H17G17 steel. That difference will be clear when fracture type will be taken into consideration. For specimens made of 50H17G17 steel the necking during thermal cycling could be neglected (because of brittle fracture) while for those made of H23N18 steel ductile fracture occurred. That is why the $W_{NS\max}$ value slightly depends on fracture type.

3. Conclusions

The analysis of the results obtained leads to the conclusions that the maximum value of W_{NS}, defined as material damage, is for a given material independent of stress and temperature (for the loading process parameters applied). It slightly depends, however, on fracture type.

The $W_{NS\max}$ value can be accepted as a constant for a given material and it is close to the specific strain work W_{0s} obtained for virgin specimens; the maximum of the W_{NS} value can thus be accepted as a failure criterion.

The validity of that failure criterion was verified for specimens examined in uniaxial stress state. That criterion can be applied only when monotonic reduction of specific strain work during the loading process occurs.

Acknowledgements

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Streszczenie

DOŚWIADCZALNA WERYFIKACJA KRYTERIUM ZNISZCZENIA OPARTEGO NA PRACY WŁAŚCIWEJ ODKSZTAŁCENIA

Różnica między wartościami pracy właściwej odkształcenia, potrzebnej do zniszczenia (w temperaturze pokojowej) próbki dziewiczej i poddanej uprzednio działaniu obciążenia (w zmiennej temperaturze) do określonej liczby cykli, została wcześniej przyjęta przez jednego z autorów za miarę uszkodzenia materiału i za kryterium zniszczenia. Te propozycje poddano weryfikacji doświadczalnej. Analiza uzyskanych wyników wykazała, że maksymalna wartość wspomnianej różnicy prac właściwych odkształcenia jest stała i niezależna od naprężenia i temperatury (dla badanych materiałów i stosowanych parametrów procesu obciążenia), może być więc uznana za kryterium zniszczenia.

Резюме

ЭКСПЕРИМЕНТАЛЬНАЯ ПРОВЕРКА КРИТЕРИЯ РАЗРУШЕНИЯ ОПИРАЮЩЕГОСЯ НА УДЕЛЬНОЙ РАБОТЕ ДЕФОРМАЦИИ

Разница между значениями удельной работы деформации необходимой для разрушения (в комнатной температуре) первичного образца и образца подвергнутого раньше действию нагружения (в переменной температуре) к определенному количеству циклов раньше принята одним из авторов мерой повреждения материала и критерием разрушения. Эти предположения подвергнуты экспериментальной проверке. Анализ полученных результатов показал, что максимальное значение упомянутой разницы удельных работ

деформации является постоянным и независящим от напряжения и температуры (для исследуемых материалов и применяемых параметров процесса нагружения); значит может быть признано критерием разрушения.

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