RELATION BETWEEN LOW CYCLE FATIGUE DATA AND THE ABSORBED SPECIFIC ENERGY

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A short review of the concept of ASPEF (absorbed specific energy till fracture) and its relation to other fracture properties is given. A model is elaborated for fatigue crack initiation and the process is related to monotonic loading based on energetical considerations. Different structural steels have been fatigued in the low cycle range and the results were used to find the expected correlations. For the present a totally analytical procedure seems to be questionable, and an experimental support is recommended.

INTRODUCTION

In the last decades of this century the interest of many engineers and scientists has been focused on the problem of fracture. Most of them dealt with the brittle kind of fracture and the validity of the developed theory - the so called fracture mechanics - has been shifted only later towards more plastic materials. L.Gillemot [1] on the contrary introduced a concept - the absorbed specific energy till fracture (ASPEF) - to characterize plastic fracture. This quantity has been mentioned by some other scientists too [2,3], but a systematic research to investigate the specific features of it and the relations with other material characteristics has been performed at first at the Technical University of Budapest. The results were summerized recently by Czoboly et al. [4]

ASPEF is a specific energy per volume concerning an infinitely small element of the specimen, where the crack nucleates after a given amount of plastic deformation. Since energy criteria became general also in fracture mechanics, it was evident that the two fracture theories - although based on different principles - can be related to each other. This was done by Radon and Czoboly [5], who calculated the usual fracture mechanics parameters by using ASPEF of the material and a characteristic dimension of the plastic zone ahead of the crack. The method has been improved and extended

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by Havas et al. [6] and its validity verified by extensive tests. [7-9]

F.Gillemot [10] found a relation between fatigue crack propagation data and ASPEF in the case of constant strain amplitude loading. Similarly, a strong correlation has been demonstrated between ASPEF and the material constants of the Paris equation by Romvári and Tóth [11] . It seems therefore that - although after simplifications - a quantitative relationship can be found among the different types of fractures, which can help to solve engineering problems.

Less attention has been devoted to the question of fatigue crack nucleation in respect of ASPEF, however, Halford [12] presented a compilation of a great amount of experimental data and Havas [13] examined the possibility of any correlation between ASPEF and fatigue life in a former work. Aim of the present paper is a review of the former results and a completition of them with new data to find relations suitable for numerical calculations.

THE APPLIED MODEL

Fatigue cracks generally nucleate at some kind of geometrical or metallurgical stress- and strain concentrator. This critical part of the specimen or structure can be modeled by the tip of a notch (Fig.1.). The local stress here exeeds very often the yield stress of the material and a loading cycle produces local plastic strain. A fatigue crack will nucleate at this point, if the plasticity of the material will be exhausted.

Across the plastic zone a small specimen suitable for studying the exhaustion of plasticity can be imagined. Such modeling experiments are well known as "low cycle fatigue tests", where alternating plastic strain is applied. A typical hysteresis loop can be seen on Fig.2., representative for the loading cycle and the meaning of the main parameters of the test as strain and stress amplitude, strain and stress range, total-, plastic- and elastic strain can be recognised. The area of the loop represents a given amount of energy accomplished by the loading force. This "input energy" increases with increasing strain amplitude.

It is supposed, furthermore, that some part of the "input energy" absorbed in the specimen will damage the micro structure resulting finally a fatigue failure. This consideration is very similar to the philosophy of ASPEF. Here too the "input energy" is regarded as a characteristic quantity concerned to a unit volume. If ASPEF has to be measured by a tensile test, the energy absorbed in the necking part of the specimen is of interest. In the close neighbourhood of the least cross section the absorbed specific energy during the test is equal to

$$W_c = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \qquad (1)$$

where σ and ε are true stress and true strain, resp. and ε_f is fracture strain.

It is obvious that only one fragment of the absorbed energy is used for damaging processes, while the greater part is dissipated as heat. However, the total absorbed energy, W_c has proved to be a material characteristic [14] .

Taking into account that a tensile test can be regarded as a low cycle fatigue test with a very high strain range, and a very short fatigue life, $N_f = 0,5$ a relation between the input energies in the case of monotonic and cyclic loading is to be expected.

TESTING METHODS AND MATERIALS

A great variety of structural steels have been involved in the experiments, which are listed in Table 1. Some of the materials originated in structures (pressure vessels, power station drums, etc) used for many years, therefore the given data should be considered only as specific values of the charge investigated. The purpose of including these data in this compilation was to increase the range of validity of the correlations, if there are any.

Original notation	Corresponding DIN Mat. No.	Test temp. °C	Remarks
C 10	1.1121	20	
C 35	1.1181	20	
CrMo 125	1.7218	20	
11523	1.0562	20	
12HIMF (charge 1)	-	20	
" (charge 2)	-	20	In service for 50000 hours
" (charge 3)	-	20	In service for 100000 hours
" "	-	540	"
" (charge 4)	-	20	Tempered
13 Cr Mo 44	1.7335	20	
"	"	500	
BHW 38 (charge 1)	-	20	In service for 100000 hours
" "	-	350	"
" (charge 2)	-	20	"

Table 1. The list of materials tested.

Tensile- and low cycle fatigue specimens were machined with a diameter of 8 and 6 mm, resp. The tests were performed at 20, 350, 500 and 540 °C, depending on the service temperature of the given structure. Both to the tensile as well to the low cycle fatigue tests the same electro-mechanical machine of 100 kN capacity was used. The cross head speed varied between 0,5 and 2 mm/min,but it was kept constant for each material.

Low cycle fatigue tests were carried out at constant strain amplitude. The hysteresis loops have been plotted periodically to monitor cyclic softening or hardening. Although this technique provides the possibility to observe macro crack initiation, the tests were continued until complete failure. The number of cycles to crack initiation were not registered. Only the total fatigue lives are given. However, it may be argued this procedure has many advantages, although they are not discussed here for shortness.

Tensile properties, as yield stress R_e, ultimate tensile stress R_m, true fracture stress R_f and true fracture strain ε_f have been determined and the values of ASPEF have been calculated. Instead of the more exact equation given in Ref. [1], a simplified formula was used:

$$W_c = \frac{R_e + R_f}{2} \varepsilon_f \tag{2}$$

which approximates the real value within ± 10 percent.

The low cycle fatigue tests furnishes the data to construct the Manson - Coffin diagram and to determine the exponent, m of the equation 3.

$$\Delta \varepsilon_{pl} N^m = C_1 \tag{3}$$

According to the considerations above, $\Delta\varepsilon_{pl}$ is equal to ε_f, if N is equal to 0,5. Therefore

$$C_1 = \frac{\varepsilon_f}{2^m} \tag{4}$$

Furthermore, the input energy of an average load cycle was determined. That means that

- the area of the loops was measured and the energy was calculated by equation 5.

$$\Delta E = \frac{8}{\pi \cdot d_0^3} \int_{d_0}^{(d_0-\Delta d)} F \, dd \tag{5}$$

F is load d is the varying diameter and d_0 is the original diameter of the specimen. This equation is an approximation, because instead of d_0^3 d^3 should be used. However the error is in our case less than 3 percent.

- the area of the stabilized loop was measured, disregarding the transient part of life as cyclic softening (hardening) or crack propagation.

Using the input energy of the half life cycle, E_f the total input energy was calculated as a product of ΔE and the number of cycles till fracture

$$E_f = N_f \Delta E \tag{6}$$

Plotting the E_f values in a log-log scale as a function of the fatigue life, a linear relation is found [12, 13, 15]. Accordingly

$$E_f N_f^n = C_2 \tag{7}$$

where n is a material constant and

$$C_2 = \frac{W_c}{2^n} \tag{8}$$

because $E_f = W_c$, if $N_f = 0{,}5$.

TEST RESULTS

Some typical examples of the results are illustrated on Fig.3. and 4. It can be seen that for the materials tested - also not shown on the Figure - the measured values fit very well on the lines according to equations 3 and 7. The values of the exponents m and n are summerized in Table 2.

Material		Temp. °C	m	n	$-\frac{m}{n}$	$\frac{n+1}{m}$
C 10		20	0,538	-0,36	1,49	1,19
C 35		20	0,460	-0,39	1,18	1,33
CrMo 125		20	0,542	-0,35	1,52	1,20
11523		20	0,596	-0,37	1,61	1,06
12H1MF	(charge 1)	20	0,650	-0,22	2,89	1,20
"	(charge 2)	20	0,671	-0,24	2,80	1,13
"	(charge 3)	20	0,658	-0,27	2,90	1,11
"	"	540	0,670	-0,29	2,31	1,06
"	(charge 4)	20	0,640	-0,22	2,90	1,22
13 Cr Mo 44		20	0,591	-0,32	1,87	1,15
"		500	0,670	-0,29	2,34	1,06
BHW 38	(charge 1)	20	0,709	-0,21	3,38	1,11
"	"	350	0,790	-0,31	2,55	0,87
"	(charge 2)	20	0,700	-0,20	3,50	1,14

Table 2. The values of the exponents m and n and their combinations

It is worth mentioning that although the values of m and n are near to 0,5 and -0,33 resp., as it is given in the literature, their deviations of these average values has a strong influence on the followings.

DISCUSSION

As mentioned earlier, one - unknown - part of the input energy damages the structure of the specimen during the test and causes fracture. This damaging part includes the energy to increase dislocation density, number of vacancies, porosity, micro cracks, etc. and also the energy to raise the local temperature. The other part of the input energy is dissipated by heat transfer and will not pay a role in the fracture process.

In the case of static tests the ratio of the damaging part and the total input energy has been proved to be constant and therefore the total input energy (ASPEF) can be used as a convenient specific value of the material in engineering.

On the supposition that a given material will fail after absorbing a characteristic quantity of energy depending only on the circumstances of loading, as temperature and loading rate, but not on the kind of loading, a constant ratio of damaging and total input energies was expected in the case of cyclic loading too. If so, then E_f should be equal to W_c andshould be independent of the strain amplitude. The positive slope of the E_f/N_f curve shows, however, that this is not true, but the ratio decreases with decreasing strain amplitude, or with other words: with decreasing strain amplitude the total input energy increases. The rate of increment can be calculated by using equations 3 and 7 as follows:

$$\frac{\Delta\varepsilon_{pl}}{\varepsilon_f} = \left(\frac{W_c}{E_f}\right)^{-\frac{m}{n}} \tag{9}$$

In Table 2 also the exponent -(m/n) is given and it can be noticed that this value varies over a wide range. Any energetical calculations can be misleading, if average values for m and n are used, that is 2/3 for -(m/n), while calculations with the actual m and n exponents provide satisfactory results. (See Fig.5.). Considering the great scatter of individual fatigue data, the points fit well on the theoretical 45° line.

The input energy in one load cycle can be expressed too by the help of equations 3, 4, 6 and 9.

$$\Delta E = 2W_c\left(\frac{\Delta\varepsilon_{pl}}{\varepsilon_f}\right)^{\frac{n+1}{m}} \tag{10}$$

Here again, application of average values for m and n recommended in the literature can be misleading. However, the variation of exponent (n+1)/m is not so great as that of -(m/n) (See Table 2)

Finally, the variation of the damaging part of the input energy can be assessed. As mentioned earlier, we suppose that only one part of the input energy is responsible for the damaging process. This should be denoted by W_d, where

$$W_d = C_3 \cdot W_c \tag{11}$$

C_3 is <1,but unknown. Assuming a uniform energy absorbtion during the fatige life, as a first approximation, ΔW_d energy is used for the damaging process in one cycle.

$$\Delta W_d = \frac{C_3 \cdot W_c}{N_f} \tag{12}$$

Using equations 3 and 4,it follows

$$\frac{\Delta W_d}{W_d} = 2\left(\frac{\Delta\varepsilon_{pl}}{\varepsilon_f}\right)^{\frac{1}{m}} \tag{13}$$

CONCLUSIONS

The energy concept provides the possibility to relate fatigue crack initiation to static material properties like ASPEF. For numerical calculations, however, the constants of the material in question should be used, since average values recommended in the literature may be misleading. Determination of the constants is possible for the present only by experiments. Further research work is carried on in the hope that an analytical solution will be elaborated.

LIST OF SYMBOLS

C_1, C_2, C_3 = material constants
d = diameter of specimen (mm)
d_o = original diameter (mm)
Δd = variation of diameter during one load cycle (mm)
ε = true strain
ε_f = true fracture strain
$\Delta\varepsilon_{pl}$ = plastic strain range
E_f = total specific input energy in the course of a fatigue test (MJ/m^3)
ΔE = specific input energy in one load cycle (MJ/m^3)
F = force (N)
m, n = exponents
N_f = number of cycles till fracture
R_e = yield stress (MPa)
R_m = ultimate tensile stress (MPa)
R_f = true fracture stress (MPa)
σ = true stress
W_c = absorbed specific energy till fracture (ASPEF) (MJ/m^3)
W_d = damaging part of input energy (MJ/m^3)
ΔW_d = damaging energy in one load cycle (MJ/m^3)

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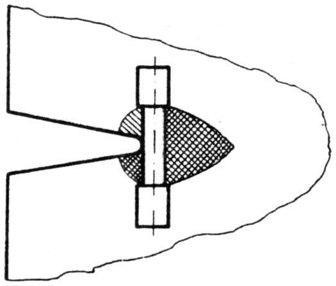

FIG.1. Plastic zone and imagined small specimen at a notch tip.

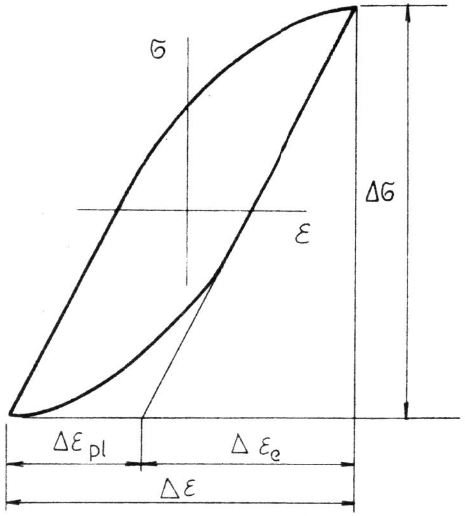

FIG.2. Typical hysteresis loop.

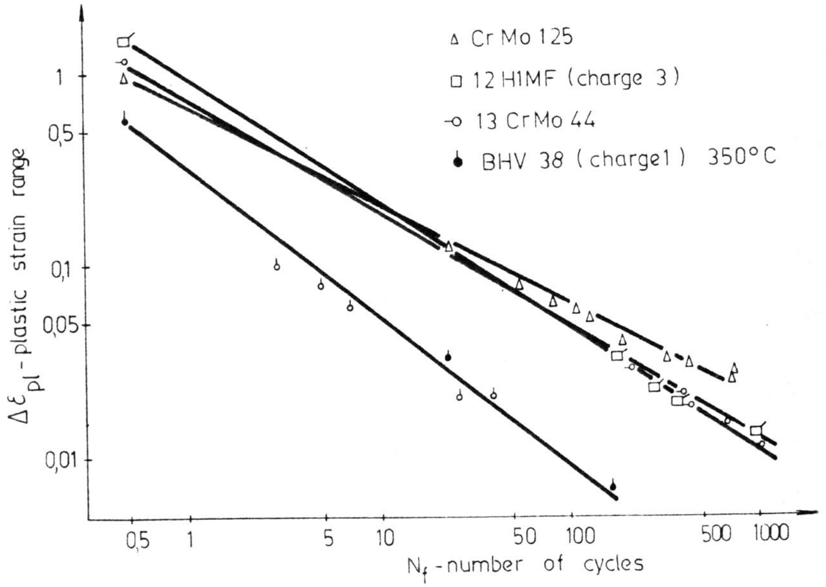

FIG.3. Manson-Coffin diagrams of some material tested

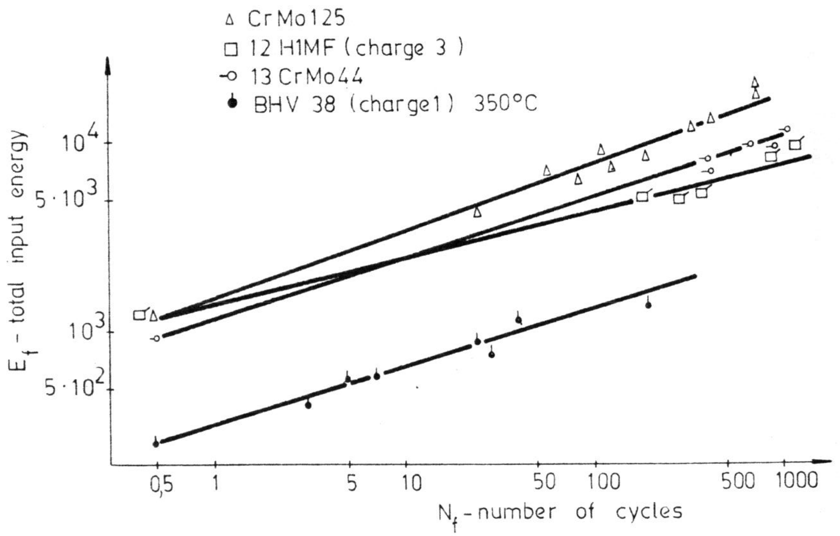

FIG.4. The total input energy of some material tested as a function of load cycle

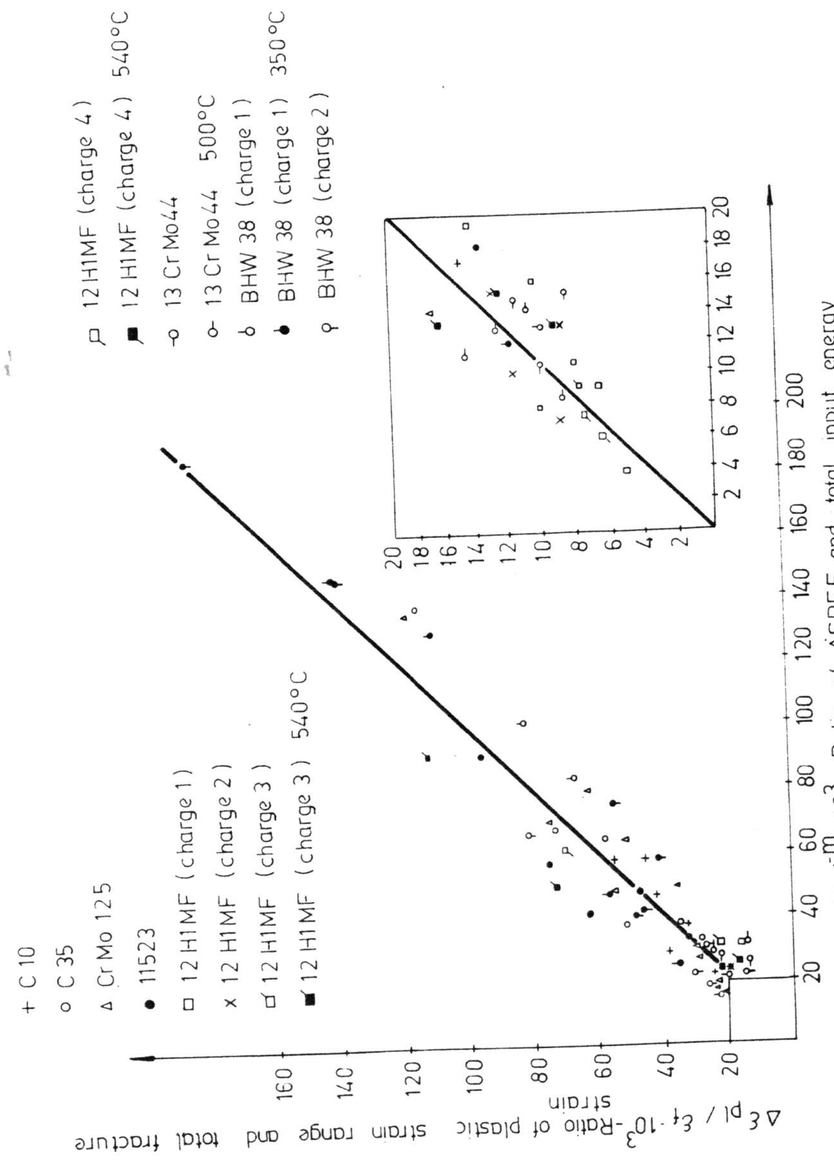

FIG.5. Comparison of strain ratio and energy ratio values according to equation 9