JUDGING THE PHENOMENON OF BRITTLE FRACTURE CAUSED BY GRAIN COARSENING, ON THE BASIS OF FRACTURE WORK

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Introduction

The phenomenon of brittle fracture can be divided into two stages. The first stage is the formation of the crack, the second is its extension.

The tests known so far generally serve for detecting the tendency to brittle fracture. If we consider any of the well-known and usual tests we shall find one common characteristic in all of them, namely, that they result in producing an indication number relating only to the given method of testing

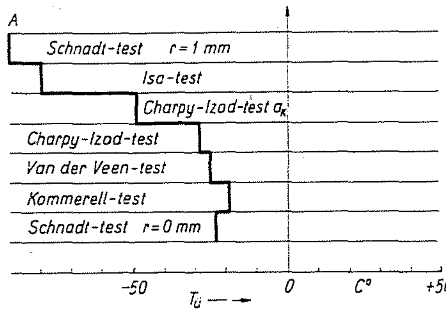

Fig. 1. Changes in temperature of brittle transition measured on various test pieces [1]

and the given test piece. It is, for instance, generally known that the result of the impact bend test depends on the size of the test piece and can at most be correlated to the brittle fracture appearing in practice. If the brittle transition temperature of a steel is decided, after various impact tests, a great variety of transition temperatures are given depending on the size and shape of the test piece (Fig. 1) [1].

It is obvious that, for a numerical evaluation of the phenomenon of brittle fracture, a test must be developed, the numerical result of which independs on the size of the test piece. The impact bend tests, the notched tensile tests, the varius notched bend tests (Van der Veen test, Tipper test, Lehigh test, etc. [2, 3, 4]), investigate on the material of a multiaxial and non-uniform state of stress the influence caused by a definite notch. With each test, however, the resulting indication number, the angle of bending, the contraction, or any other number characteristic of the strength or plasticity of the material will be characteristic only for the given test piece sizes. Therefore, first of all, an indication number must be found for which the law of proportionality will be valid in the multiaxial and non-uniform stress state as well; i.e., geometrically similar test pieces must yield the same indication number.

The law of proportionality for testing materials had been drawn up by Kick and Barba as early as the end of the last century. According to the Kick—Barba law, the work necessary for shaping geometrically similar test pieces of the same material is proportional to the volume of the test piece. A slightly different drafting of the original Kick—Barba law will give the following: the specific deformation work necessary for giving test pieces of the same material a deformation of identical size, will also be identical.

The term "specific deformation work" means the work necessary for the deformation of an elementary volume assigned at any cross section of the test piece. Let us have, according to Fig. 2., in one cross section of a simple, cylindrical tensile test piece the assigned volume V_0, then the specific deformation work will be:

$$A_c = \int \frac{PdL}{V_0} = \int \sigma \, d\delta \tag{1}$$

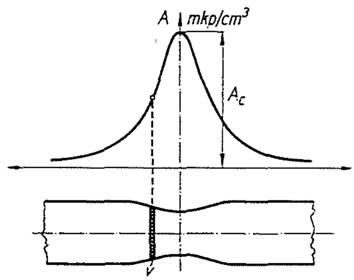

Fig. 2. Change of specific deformation work along the longitudinal axis of a tensile test piece

where σ is the stress related to the original cross section, and δ is the effective elongation of the cross section examined. Choosing the examined cross section at the place of fracture, we shall obtain the specific fracture work necessary for breaking the test piece:

$$A_C = \int_0^{\delta_c} \sigma \, d\delta \tag{2}$$

where δ_c is the effective elongation appearing in the cross section of the fracture, which can be expressed by contraction in the following way:

$$\delta_c = \frac{\psi}{1 - \psi} \tag{3}$$

The work needed for the deformation of the volume elements of the test piece along the longitudinal axis of same will also be shown in Fig. 2. The specific fracture work can be easily computed from the constants determined in the course of the tensile test (5.6.):

$$A_c = \frac{\delta_e}{3}(\sigma_F + 2\,\sigma_B) + 4{,}6\,\sigma_B(1+\delta_e)\lg\frac{1+\delta_c}{1+\delta_e} + \sigma_B(1+\delta_e)^2\left[\frac{1}{1+\delta_c} - \frac{1}{1+\delta_e}\right] \tag{4}$$

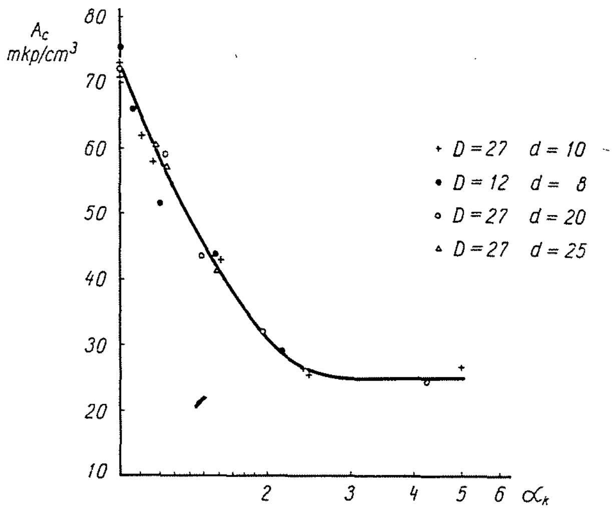

Fig. 3. Change of specific fracture work plotted against the stress concentration factor, measured on test pieces of different diameter and notched test pieces

where σ_F is the yield point, σ_B the tensile strength, δ_e the uniform elongation, δ_c the effective elongation appearing at the fracture, according to Formula 3.

When testing a variety of structural materials (steel, aluminium, copper) it can be stated that specific fracture work is independent of the size of the test piece [7]. This rule can be generalized for notched test pieces as well, and is valid even between much wider limits than the original Kick—Barba law. The fracture work needed for the deformation of two differently sized test pieces will be equal not only when the two pieces are geometrically similar, but also when the stress concentration factors characteristic of the extent of notching are identical. The value of the stress concentration factor (a_k) will be unequivocally determined by the diameter D of the test piece, the diameter d of the cross section weakened at the place of the notching and the bend radius ϱ of the notching. The fracture work of two notched test pieces will be identical with an exactness satisfying the needs of practice, if their stress concentration factors and inherent factors influencing brittle fracture are the same. To check this law of proportionality on various structural materials, an extensive series of tests have been carried out by GILLEMOT [8].

As an example, in Fig. 3, the results of a series of experiments made on standard steel C 35 (plain carbon steel with 0.35% C content) are presented. The test-pieces were made with two different diameters and with four notches having different depths. Independent of other dimensions of the test piece, the numerical values of the specific fracture work will lie on the same curve, if the specific fracture work is measured as plotted against the stress concentration factor. Accordingly, a generalized form of the law of proportionality can be drafted in the following: the specific fracture work of notched test pieces with identical stress concentration factors will practically always be the same for one given material. This generalized law of proportionality will give possibility for working out a physically well based brittle fracture testing method.

Examining brittle fracture on the basis of contraction work

The work of specific deformation consists of two parts: that of elastic deformation work, and the work of plastic deformation. It is obvious that a material is brittle when the total work of deformation is equal to the work of elastic deformation, i. e.,

$$A_c \approx A_p \tag{5}$$

where A_p is the elastic deformation work.

The work of elastic deformation is

$$A_p = \frac{\sigma_F^2}{2E} \tag{6}$$

where σ_F is the yield point, E is the modul of elasticity. The work of elastic deformation is very small and can be neglected if compared to the plastic deformation work and, to make it more simple, the point where the work of deformation is approximately zero, can be considered as the criterion of brittleness.

Consequently, the specific deformation work is an indication number which helps us to construct a law of proportionality that can be used in practice: the condition of brittle fracture is simply the fact that the specific deformation work is approximately equal to zero.

Examining the specific fracture work of structural materials on notched test pieces, we find that specific fracture work plotted against the stress concentration factors can be principally of two types (Fig. 4). With one group of structural materials, the specific fracture work will be reduced down to zero (curve *B* in the diagram); with other materials the curve of the specific fracture work approaches some limit value asymptotically (curve *A*). The tests were generally carried out only untill the stress concentration factor $a_k = 6$, notches with higher stress concentration factors cannot be made with any certainty. The character of the curves, however, was quite well formed till $a_k = 6$; therefore, the investigation of sharper notches does not seem to be absolutely necessary.

The specific deformation work in the function of the stress concentration factor therefore will enlighten us on the point whether, or not, a certain mate-

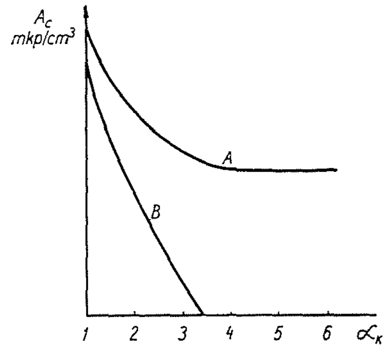

Fig. 4. Fracture work of various structural steels plotted against the stress concentration factor (sketch)

rial is inclined to brittle fracture in the multiaxial and non-uniform state of stress. The form of the curves characteristic of the material will naturally also depend on the temperature of testing, the speed of the change of stress and the microstructure of the structural material.

In the following we shall review the influence of grain growth in a number of examples. We wish to investigate the correlation between A_c and grain size on unnotched test pieces; it is based on measurements that had been taken in the course of testing. Further, the correlation between A_c and a_k on notched test pieces will be dealt with, the materials being fine- and coarse-grained; this is based on the data of GILLEMOT [9].

Test materials

The material for unnotched test pieces was a relatively pure Ni, TL3 ferrit chrome steel, Cu—Ti and C 10 low carbon standard steel. Composition of each material is given in Tables 1, 2, and 3.

For notched test pieces the experiments were carried out with standard steels marked A 37.21, A 50.21; a manganese-titanium steel corresponding

Table 1

Material	Fe%	Cu%	Si%	As%	Pb%	Co%	Zn%	P%	Mn%	Ti%
Ni	0.008	0.021	0.008	0.005	Ny	0.09	0.01	0.003	0.005	—

Table 2

Material	As%	Ag%	Fe%	Pb%	Sb%	Bi%	Sn%	Ni%	Ti%
Cu-Ti	0.003	0.0005	0.008	0.0001	0.0003	0.0001	0.0001	0.018	1.91

Table 3

Material	C%	Mn%	Si%	Cr%	Ni%	P%	S%
TL3	0.20	0.90	0.50	13.00	2.0	0.04	0.04
C 10	0.11	0,44	0.23	0.20	0.07	0.022	0.04

Table 4

Material	Cu%	C%	Mn%	Si%	Al%	Ti%
A 37.21	n.a.	0.13	0.39	ny.	n.a.	—
A 50.21	n.a.	0.29	0.57	0.02	n.a.	—
MTA 50	n.a.	0.19	1.20	0.40	0.1	0.03
Steel X	0.49	0.19	1.5	0.50	n.a.	0.14

Note: 1. according to standards S and P
2. n.a. = not analyzed.

to the Hungarian standard MTA 50; further, a non-standard composition steel marked X. Composition of each kind of steel is given in Table 4.

Influence of grain size on brittle fracture in the case of polished test pieces

To determine the sensitivity to brittle fracture we carried out static tensile tests after grain coarsening heat treatment made at different temperatures. Specific deformation work in the function of grain diameter is shown in Figures 5, 6, 7 and 8. In case of a relatively pure Ni (Fig. 5) the growth of grain diameter from 0.03 mm to 0.175 mm results in the reduction of fracture work from 80 mkp/cm^3 to 68 mkp/cm^3. With TL3 material (Fig. 6) the fracture work will decrease from 72 mkp/cm³ to 53 mkp/cm³, when the grain diameter increases from 0.04 mm to 0.125 mm.

The specific fracture work of the relatively pure Ni and the TL3 ferrit chrome steel will change in the same way. With the growth of the grain diameter, A_c will decrease linearly in both cases. The result obtained on the influence of grain diameter in these two materials is the most significant, as neither

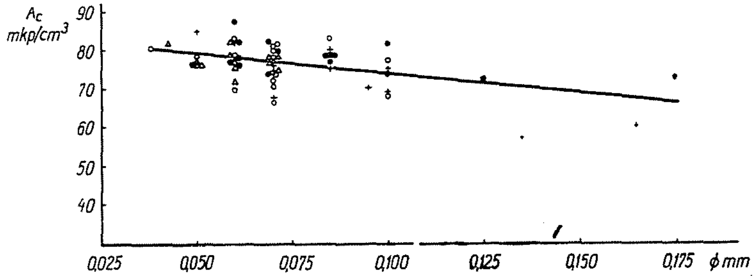

Fig. 5. Change in the specific fracture work of a relatively pure Ni, plotted against grain diameter

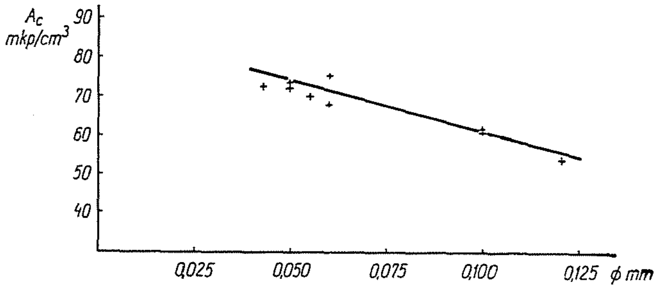

Fig. 6. Change of specific fracture work of a TL 3 ferrit chrome steel plotted against grain diameter

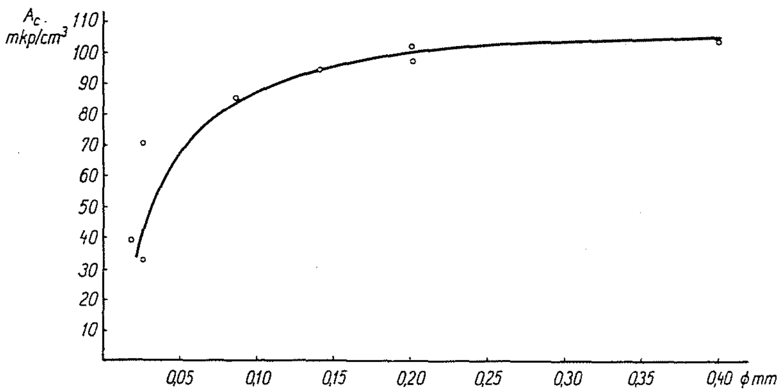

Fig. 7. Change of specific fracture work of 97.99% Cu—1.91% Ti alloys plotted against grain diameter

recrystallization, nor segregation appears in the course of grain coarsening heat treatment. Thus, the influence of grain size can clearly be observed without the disturbing effect of any other structural change.

We find a different correlation from the preceding when we take the Cu—Ti and C 10 materials. With both materials a compound appears in the course of heat treatment and its influence will also be marked, besides the changes in the grain sizes. Results measured in the Cu—Ti alloys can be seen in Fig. 7. According to this, the growth of the grain diameter from 0.05 mm to 0.40 mm will result in the growth of fracture work from 30 mkp/cm^3 to 100 mkp/cm^3. Results measured on C 10 material show (Fig. 8), that, when the

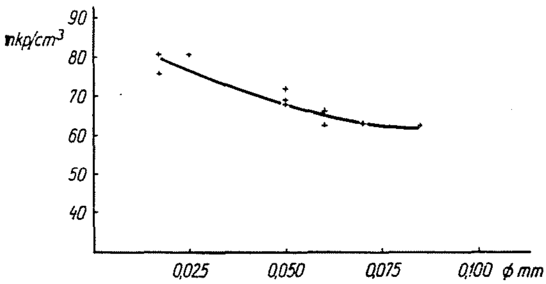

Fig. 8. Change of specific fracture work of C 10 low carbon steel against grain diameter

grain diameter grows from 0.015 mm to 0.085 mm, the fracture work will be reduced from 80 mkp/cm^3 to 62 mkp/cm^3. The correlation between fracture work and grain diameter is in neither case linear.

It can be seen from these two examples that with alloys where some kind of heterogeneous structure is formed after heat treatments applied for producing various grain sizes, the value of the specific fracture work will depend on the properties and quantity of the single phases. Its value will be mainly decided by the relative position, dispersion, shape and quantity of the crystals in the hard phase.

Influence of grain size on brittle fracture in the case of notched test pieces

All four types of steels were tested in a normalized state, and at grain coarsening at 1300° C. Static tensile tests were carried out on test pieces with two kinds of grain diameters and with different notches to determine the sensitivity for brittle fracture. The values of fracture work plotted against the stress concentration factor are shown in Figs. 9, 10, 11 and 12. The specific fracture work of soft steel A 37.21 in its annealed state, measured on polished test pieces is 66 mkp/cm^3 and, even in the case of very sharp notches, 30 mkp/cm^3. Following a grain coarsening heat treatment, however, the fracture work will be, in the case of a polished test piece, ($a_k = 1$) 48 mkp/cm³ and, even with sharp notches it will be still 10 mkp/cm³. In the case of this steel the discrepancy between the annealed and grain coarsened state is very great.

The grain coarsened state of the steel A 50.21 does not greatly differ from the original annealed state in the case of sharp notches. With this material and with $a_k = 5$—6, fracture work is only 6—7 mkp/cm³.

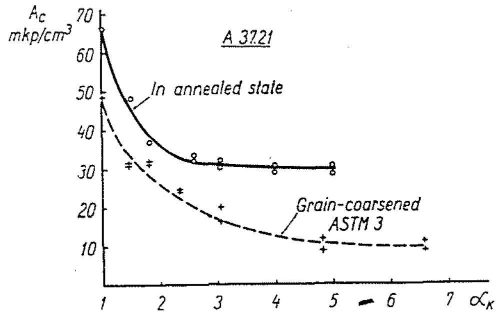

Fig. 9. Specific fracture work of soft steel A 37.21 plotted against the stress concentration factor, in annealed and grain-coarsened state

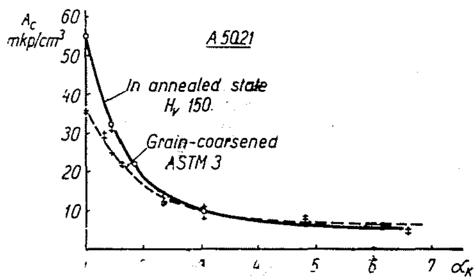

Fig. 10. Specific fracture work of steel A 50.21 plotted against the stress concentration factor in annealed and grain-coarsened state

The specific fracture work of the manganese-titanium steel marked MTA 50 in annealed state measured on polished test pieces is considerably higher than that of the two preceding materials, round about 85 mkp/cm³. In grain-coarsened state the value of fracture work will not sink, even with the sharpest notch under 12—17 mkp/cm³.

The test steel marked X, which was examined as specially inclined to brittle fracture, shows an extremely high specific fracture work in normalized state, measured on polished test pieces. Also in normalized state, measured at room temperature with $a_k = 6$ notch, its specific fracture work will decrease only to 30 mkp/cm³, but the declining character of the curve can be expected to continue, and does not approach of the curve can be expected to continue, and does not approach a given limit value asymptotically. The steel is extremely sensitive to grain coarsening and will be absolutely brittle already at a notch with 2.7 stress concentration factor in grain-coarsened state.

The diagrams of the above materials make it obvious that the brittle fracture sensitivity of the steel A 37.21 strongly increases with grain coarsen-

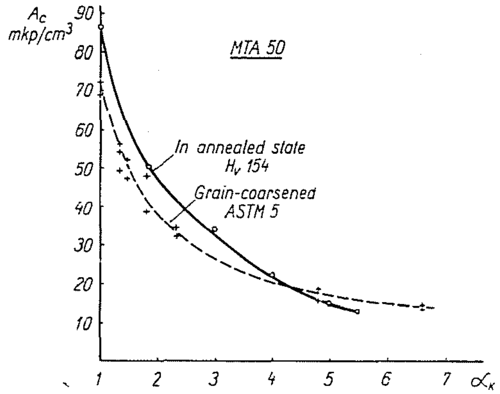

Fig. 11. Specific fracture work of steel MTA 50 plotted against the stress concentration factor in annealed and grain-coarsened state

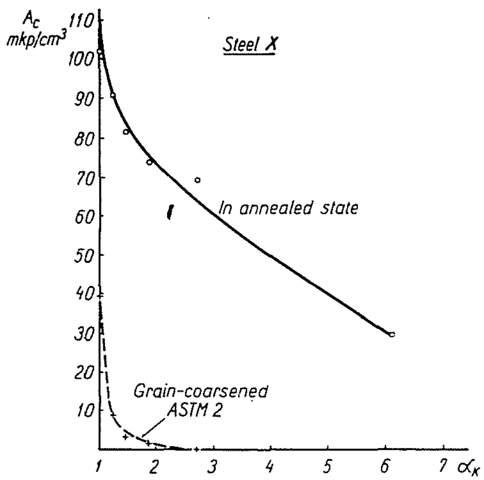

Fig. 12. Specific fracture work of experimental steel X plotted against the stress concentration factor in annealed and grain-coarsened state

ing; yet in constructions working at room temperature there is no danger of brittle fracture. Steel MTA 50 at room temperature is not inclined to brittle fracture after any kind of treatment; steel A 50.21 is inclined to brittle fracture in annealed and grain-coarsened state alike, but will not grow entirely brittle; whereas the experimental material marked X will grow brittle after grain coarsening even at room temperature.

Let us now consider from Figs. 9, 10 , 11 and 12, how the value of breaking work will change with stress concentration factors $a_k = 1$, $a_k = 1.7$ and $a_k = 6$, in annealed and grain coarsened state.

No. Material	in annealed state A_c mkp/cm³			grain-coarsened A_c mkp/cm³		
	$a_k = 1$	$a_k = 1.7$	$a_k = 6$	$a_k = 1$	$a_k = 1.7$	$a_k = 6$
1. A 37.21	66	40	30	48	28	10
2. A 50.21	55	25	6	36	22	6
3. MTA 50	85	55	12	72	44	15
4. Marked X	113	78	30	39	2	0

Inherent stresses of a construction producing arbitrary stresses cannot be determined in advance, but the stress concentration factor a_k can well be approximated. If, for a given material, the correlation $A_c - a_k$ is known, after determining the stress concentration factor, the value A_c belonging to it can be found from the correlation. If the value of the specific fracture work thus found is higher than a given value, it can be stated that with that stress concentration factor and for a given material there is no danger of brittle fracture yet. For example, according to the above Table, there is no danger of brittle fracture in the case of steel X with $a_k = 1$ in annealed or grain-coarsened state, whereas with $a_k = 1.7$, after grain coarsening, brittle fracture ensues. It can generally be stated that only such structural materials give full safety, the specific breaking work of which, as plotted against the stress concentration factor, will asymptotically approach a given limit value.

Summary

The tendency towards brittle fracture can be numerically characterized by the specific fracture work. Precondition of brittle fracture is that the specific fracture work is equal to zero.

The multiaxial and non-uniformly dispersing states of tension appearing on constructions can be considered by choosing the stres sconcentration factors of notched tensile tests. Thus the correlation $A_c - a_k$ determined for the material treated in a given way will always reveal whether there exists a danger of brittle fracture.

The danger of brittle fracture is always increased by the coarsening of the grain structure, as the value of specific fracture work decreases with the growth of grain size in polished and notched test pieces alike.

In the case of identical stress concentration factors, the material with coarser grain is more inclined to brittle fracture. With certain materials the discrepancy between the values of fracture work for different grain sizes can be extremely large.

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