INVESTIGATION OF DIE STEELS

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1. Introduction

Loading of dies

The loading of dies may very much differ in character and, accordingly, die life depends on many factors. The load on dies may be slow, of a static nature, or dynamic impact-like. The character of loading is, by necessity, always repetitive and, in general, of a zero value initially, if the die is not prestressed, whereas the load on prestressed dies may be tensile-tensile, tensile-compressive, or compressive-compressive, depending on the extent of prestress. Dies must be, therefore, dimensioned to fatigue, except where the load is from zero to tension or zero to compression as the zero start fatigue limit is generally identical to the yield point, thus in such a dimensioning the yield point may characterize the material.

Die fracture, however, is not necessarily due to fatigue. If the die has stress concentration points, the multiaxial stress condition in their area and the rate of loading may lead to brittle fracture.

The third factor affecting die life is the time of contact between die and work. If this period is excessive then, upon the increased temperature of the work, the die may turn austenitic in a thin layer which, in turn, may harden after the removal of the work. The thin austenitic layer may then crack during the next blow and, thereby, initiation of a propagating crack will be formed.

Last but not least, the life of a correctly dimensioned die made use of with the appropriate technology is governed by wear. The extent of wear depends on the surface pressure applied to the die, on the friction coefficient and, as demonstrated by S. A. TOBIAS [1], on the contact time.

Thus die life is determined fundamentally by four different load types:

1. fatigue,
2. brittle fracture,
3. hardening within a thin layer, and
4. wear.

The last two of the four factors can be influenced, above all, by a correctly selected technology. Omitting here the details of all the technological factors, it will suffice to say that, obviously, a reduction of the contact time and friction coefficient should be endeavoured. The latter can be achieved by good lubrication, and the use of scale-free or minimum scale surface work pieces. The phenomena of fatigue or brittle fracture depend on the technological factors to a lesser degree. Their study is, therefore, feasible by the elaboration of a material testing technique whereby the steel type most suitable for the purpose and its best heat treatment method is readily predetermined through laboratory investigations. Obviously, tool steels cannot be defined by a single strength characteristic as both fatigue and brittle fracture phenomena are greatly affected by the plastic properties of the material. Brittle materials such as carbides represent an exception, if the load on the die varies only between zero and compression.

The plastic properties of the material are best characterized by the specific fracture energy. The latter has several peculiar characteristics which permit the unequivocal determination of the die material quality by means of only two data: yield point (fatigue limit) and the specific fracture energy proper.

2. Specific fracture energy

The idea of specific fracture energy was introduced by Ludwik. Some of its typical properties, as those of a material testing index, were studied by K. Matthaes [2], who found that the specific fracture energy of certain structural steels would be independent of the tempering temperature within a wide range. Our previous investigations support the validity of this statement in relation with temper-grade carbon steels, chromium-nickel and manganese steel types [3]. Generally, however, it is not quite true in the case of steels where carbides are precipitated in the course of tempering [4, 8].

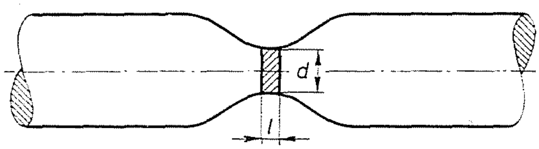
According to definition, specific fracture energy (W_c) is:

$$W_c = \int \sigma \cdot d\varepsilon \tag{1}$$

where σ is the true stress and ε indicates the true strain. It follows from Eq. (1) that the specific fracture energy is simply the correctly scaled tensile diagram area of true stress vs. true strain.

Determination of the specific fracture energy when using an unnotched specimen is illustrated in Fig. 1, together with the proof of Eq. (1). At the least cross-section, determination of the true strain is by diameter measurement. The stress and strain values vary along the cross-section of the necked specimen and, therefore, both the strain and the true stress defined by diameter measurement represent only a mean value related to the cross-section. It can be experimentally proved, nevertheless, that such a determination of the specific fracture energy is independent of the specimen dimensions within a wide range [5].

Miner assumed as early as in 1945 that a crack would be formed if an elementary material volume absorbed an energy of W_c quantity, characteristic of the material. Miner's hypothesis was confirmed by tensile-compressive experiments, and a low-cycle fatigue test series performed with constant true stress amplitudes [6]. The same statement was verified by HAVAS [7] through low-cycle fatigue tests conducted with constant strain amplitudes. In his



$$W = \int_0^{\varepsilon_F} \frac{F \cdot dl}{V} = \int_0^{\varepsilon_F} \frac{F \cdot dl}{A \cdot l} = \int_0^{\varepsilon_F} \sigma \cdot d\varepsilon \, [mkp/cm^3]$$

$$\sigma = \frac{F}{A}; \; d\varepsilon = \frac{dl}{l}; \quad \varepsilon = \ln \frac{l}{l_0} = \ln \frac{d_0^2}{d^2}$$

Fig. 1. Determination of the specific fracture energy W_c

experiments, HAVAS studied C-35 mild steel tempered in two different ways. The specific fracture energy of the steels tested was, independently of the tempering temperature, $W_c = 110$ mkp/cm^3 although their yield points differed. Still, in spite of these different yield points, the energy absorbed until crack initiation was the same: 110 mkp/cm^3 in both cases. So the conclusion may be arrived at that a crack will be formed when the material has absorbed its characteristic specific fracture energy W_c during one or more loadings.

Thus there are two indices required to characterize steels: a strength value for die dimensioning which may be either the yield point or the fatigue limit corresponding to the type of load, and the specific fracture energy which is an index characteristic of the crack produced either by brittle fracture or fatigue. The higher the specific fracture energy value, the longer the expected die life.

3. Optimum heat treatment of tool steels

The yield point will decrease with increasing tempering temperature, while the specific fracture energy will remain more or less constant [4]. Since, according to definition, the specific fracture energy is equal to the plastic deformation energy absorbed until crack initiation. The specific fracture energy of quenched tool steels is obviously zero. Thus the specific fracture energy will increase from zero to a certain value as a function of the tempering temperature, then it will stay more or less constant within a rather wide range of tempering temperature. Variation of the specific fracture energy and yield point of a CrNiMo steel vs. tempering temperature is shown in Fig. 2 [8]. As revealed by this diagram, maximum specific fracture energy is obtained by tempering at a temperature of 350 to 420 °C which defines, at the same time, the yield point as well. Generally, that temperature may be considered as most favourable for tempering, where a maximum specific fracture energy value is associated with the maximum yield point.

The effect of tempering was investigated on 10 different die steels by using the method described above. The chemical composition of the steels tested is shown in Table 1, while the temperature and duration of tempering, and the mechanical properties obtained are presented in Table 2.

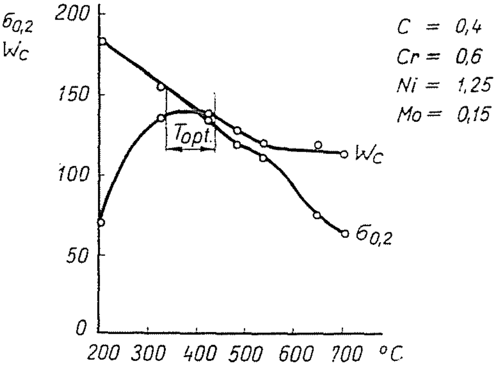


Fig. 2. Variation of the specific fracture energy and yield point of a CrNiMo steel vs. tempering temperature [5]

Table 1

Steel type	Chemical composition							
	C%	Si %	Mn %	Cr %	Ni %	Mo %	V %	W %
NC 6	0.25	0.23	0.81	0.88	3.45	0.06	—	—
NC 25k	0.27	0.16	0.65	1.67	2.51	0.16	—	—
NCMo 1	0.36	0.24	0.68	0.98	1.03	0.24	—	—
NK	0.46	0.34	0.59	0.80	1.65	0.31	—	—
K 4*	1.00	0.20	0.35	1.45	—	0.08	0.20	—
CMo 4	0.44	0.30	0.68	1.04	—	0.20	—	—
CrV 135	0.34	0.24	0.64	0.95	—	—	0.15	—
W 3	0.27	0.24	0.29	2.60	—	0.28	0.32	4.20
W 4	0.33	1.11	0.31	1.31	—	—	—	1.89
H 13 (AlSi)	0.34	1.20	0.44	5.00	—	1.22	1.10	—
X 32 CrMoV 33	0.28	0.35	0.26	2.55	0.32	2.55	0.60	0.50

* Not suitable because of the low specific fracture energy

Table 2

Steel type	Tempering temperature °C	Tempering period, h	$\sigma_{0.2}$ kp/mm²	W_c mkp/cm³
NC 6	440—640	0.5—24	110—60	145—120
NC 25k	380—640	1—24	130—65	150—120
NCMo 1	280	1—10	152	140—160
	400	0.5—5	140	155—145
	520—720	0.5—24	120—50	140—115
NK	640	1—10	95—80	110
	580	1—10	125—115	90—100
	520	5—50	135—130	70—80
CMo 4	640	0.5—3	100—85	130
	580	5—10	100—90	125—130
	520	24—120	115—80	120—125
CrV 135	520—700	0.5—100	120—50	100—115
W 3	580	1	150	150—160
	580	10	145	150—170
	520	10—24	150—152	155
	640	0.5—1	130—135	130—140
W 4	380	3	170	120
	520	10	140	125
	580	3	130	125—130
H 13 (AISI)	520	24—36	180—175	175—160
	580	1—2	165—175	165
	640	0.5	140—155	130—140
	720	0.5—10	85—60	110—50
X 32 CrMoV 33	520	8—12	155	140—150
	580	1—5	155—160	150—155
	640	0.5	155	140
	400	1—100	145	110—120

As revealed in Table 2, specific fracture energy as a function of the tempering temperature is not constant as found by K. MATTHAES in the case of structural steels.

From the aspects of specific fracture energy and yield point, the most advantageous values were rendered by steels W-3 and H-13. The American steel type H-13 is being now produced in Hungary by the Csepel Works, as steel SÜ 1.

4. Examination of brittle fracture phenomena with notched samples

For testing the plasticity of steels, including die steels, the most widely accepted method is the Charpy test or any other similar test technique. Notched impact-bending test results, however, can only be compared if the sizes of specimens and the extent of notches are identical. Thus, the law of proportionality does not apply to notched samples and, therefore, the specific impact energy expressed in mkp/cm^2 will characterize only the specimen, but

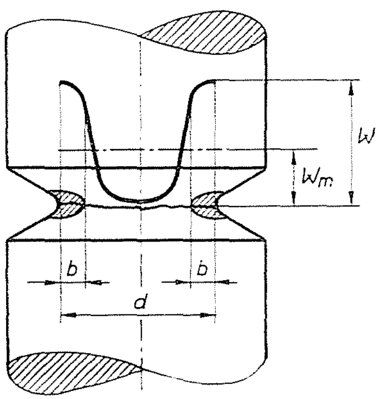


Fig. 3. The law of proportionality for notched specimens

cannot offer direct information on the service conditions. For this reason, a material testing method whereto the law of proportionality would apply had to be elaborated. By means of the specific fracture energy, it was readily possible to find the law of proportionality for notched tensile test samples. The principle is illustrated in Fig. 3. If the notch is sharp enough then, due to the multiaxial and nonuniform stress in the specimen, only an annular part of width b will undergo plastic deformation, whereas in the vicinity of the axis of the sample there will be only elastic deformation. The crack will propagate, when the fracture energy W_c is absorbed in the small volume subject to plastic deformation. It may be assumed, therefore, that at the instant immediately before crack initiation the distribution of specific energy will correspond to that outlined in Fig. 3. If the zone of plastic deformation is small enough, then, as a first approximation, it may be assumed that the specific energy absorbed therein is almost constant. Since in the course of measurement, according to the method described above, the specific strain and the true stress values can be determined only for the average cross section, the specific energy W_m thus measured will be, obviously, nothing but the specific fracture energy related to only the mean value of the total volume. In the environment of the notch root, the volume of a part of height l is

$$\frac{d^2 \pi}{4} l \tag{1}$$

On the other hand, the volume of the annular ring wherein the specific energy of a W_c magnitude, characteristic of the material, had been absorbed, will equal $b \cdot d \cdot \pi \cdot l$. It follows that the mean specific energy related to the notched specimen is

$$W_m \cdot \frac{d^2 \pi}{4} \cdot l = W_c \cdot b \cdot d \cdot l \cdot \pi \tag{2}$$

According to the experiments, the width of the plastic zone is proportional to the radius of the curvature (ϱ), that is

$$b = c \cdot \varrho. \tag{3}$$

It follows from Eqs (2) and (3) that

$$W_m = 4c \frac{\varrho}{d} W_c. \tag{4}$$

Since W_c is constant for any given material, it is obvious that in the course of the measurements, independently of the specimen dimensions, the same W_m value will be obtained if $\frac{\varrho}{d}$ is constant. This means that the W_m value obtained for geometrically similar samples is constant and independent of the specimen dimensions, if the samples are tested at an identical rate of strain. Deformation of notched samples along the cross-section will continuously vary and, therefore, the rate of strain can only be determined as an average.

Our experiments revealed [10] that the strain (L) of the notched samples was proportional to the notched diameter (d) and to the reduction of area (ψ). Expressing the reduction of area by the true strain, on the basis of the law of volume constancy we get

$$L = k \cdot d_0 \cdot \psi = k \cdot d_0(1 - e^{-\varepsilon}) \tag{5}$$

where k is a factor of proportionality. Differentiating Eq. (5) with respect to time, and taking into account that the rate $u = \frac{dL}{dt}$, we obtain

$$u = \frac{dL}{dt} = k \cdot d_0 \cdot e^{-\varepsilon} \cdot \frac{d\varepsilon}{dt}. \tag{6}$$

From Eq. (6) it follows that in the tensile test of two geometrically similar samples, the specific rate of strain will only be constant if $\frac{u}{d_0}$ is constant[11]. This rule together with the law of proportionality derived above, may be illustrated by the following example:

Be the thickness of the die to be tested 80 mm, the form factor of its notch $\alpha_k = 2$, and the speed of the die in the instant of blow 4 m/sec. A behaviour identical to that of this die will be exhibited by a specimen of diameter $d = 20$ mm, where a notch of similarly $\alpha_k = 2$ form factor should be made. Fracture of the specimen should be, however, performed at a rate of only 1 m/sec in course of the tensile test, since the diameter of the specimen is four times less.

The validity of the law of proportionality derived above was verified by a number of experiments [12] which proved that, conforming to this law, the transition temperature of brittle fracture can be determined for samples of any optional form factor, by means of samples quite different in dimensions but geometrically similar. This, in turn, made possible the investigation of brittle fracture by small-scale tests. These investigations involved the die steels presented in Table 1, after tempering considered as the optimum heat treatment. One of the experimental data is illustrated by Fig. 4. This diagram illustrates the brittle fracture inclination of steel W-3, vs. temperature, load rate, and notch. The full line indicates dynamic tests performed at a rate of 5.6 m/sec, which corresponds to the usual impact speed of the Charpy equipment. Samples of an $\alpha_k = 1.27$ stress concentration factor, when

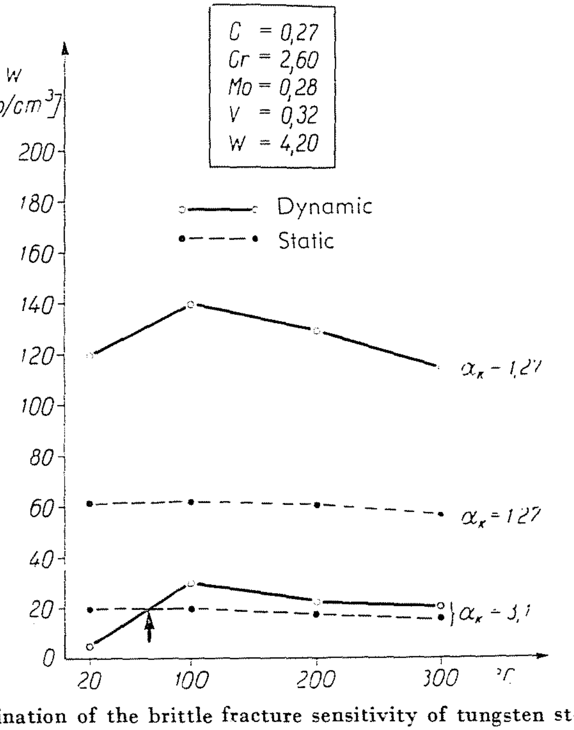


Fig. 4. Examination of the brittle fracture sensitivity of tungsten steel W-3

fractured dynamically, absorb a greater amount of mean specific energy until fracture, than under static tensile conditions. In the case of $\alpha_k = 3.1$ notched samples, the two curves intersect each other at the temperature indicated by the arrow. So there is a limit where static loading is more dangerous from brittle fracture aspects, than dynamic loading might be. The sharper the notch, the lower the temperature, where the curves of static and dynamic loading will intersect each other. This finding was confirmed by a great number of experiments performed with structural steels. This figure reveals that steel W-3 will become brittle at room temperature, in the case of 3.1 notches, whereas preheating of the die will eliminate the liability to brittle fracture.

Summary

Apart from heat effects and wear, the fracture of dies may be attributed to the following two reasons:

— fatigue, and
— brittle fracture.

Both loadings can be characterized by a strength index (yield point or fatigue limit), and by an index characteristic of the plasticity of the material (specific fracture energy). By means of these two indices the heat treatment resulting in the maximum value of both may be determined. On this basis the material quality most suitable for the purpose, and the most favourable tempering temperature can be selected. Brittle fracture is studied by using notched specimens, for which a law of proportionality can be derived, whereby the brittle fracture sensitivity can be examined under conditions corresponding to service.

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