FRACTURE TOUGHNESS OF CAST STRUCTURES

P. Uggowitzer, M.O. Speidel*

The fracture toughness of coarse two-phase alloys depends strongly on the morphology of the two phases. Based on the contiguity of the phases a rule of mixture for the fracture toughness of such alloys is proposed.

INTRODUCTION

A lot of technically important cast alloys are characterized by a coarse two-phase** micro-structure (for instance AlSi-alloys, α/β-brass, Sn-bronzes, Al-bronzes,...). Generally these alloys are a combination of brittle phases (low fracture toughness) and ductile phases (high fracture toughness).

An interesting and still unsolved problem is that of predicting the fracture toughness of such two-phase alloys from the properties of their constituent phases. In the present work an attempt is made to consider the effect of phase contiguity on the fracture toughness of two-phase alloys by means of a simple model. It is hoped that this approach will provide some insight into the fracture-composition relations.

** For the present purpose coarse two-phase structures are defined as alloys where the size of the two phases is of the same order of magnitude as the grain size of poly - crystalline alloys, i.e. 10 - 500 μm. Thus, precipitation-hardened and dispersion-hardened alloys are not considered.

* Institute of Metallurgy, Swiss Fed. Inst. of Technology, Zurich, Switzerland

BASIC CONSIDERATIONS - A RULE OF MIXTURE

Composite of plates

The oldest and simplest model of a two-phase composite is made up of laminated plates as shown in Figure 1.

We assume that the α-phase has a high fracture toughness and the β-phase has a low fracture toughness. As a measure of fracture toughness we use the J-integral J_c. Assuming that such a statically loaded composite contains a crack and assuming that this crack will preferentially propagate through the phase with lower toughness, we can calculate the fracture toughness of a composite in a simple way. On the condition that the fracture toughness of the composite is dependent on the specific surface of the fractured α- and β-phase, we obtain

$$J_c^c = J_c^\alpha A_A^\alpha + J_c^\beta A_A^\beta \qquad (1a)$$

When the phases are arranged in series (Fig. 1) the crack will propagate only through the phase with the lower toughness ($A_A^\alpha = 0$, $A_A^\beta = 1$). The toughness of the composite is given simply by the toughness of the β-phase

$$J_c^c = J_c^\beta \quad \text{(in series)} \qquad (2a)$$

When the phases are parallel, the α and the β-phase will be broken according to their volume fraction ($A_A^\alpha = V_V^\alpha$, $A_A^\beta = V_V^\beta$). The fracture toughness of the composite then depends on a linear rule of mixture.

$$J_c^c = J_c^\alpha V_V^\alpha + J_c^\beta V_V^\beta \qquad \text{(in parallel)} \qquad (2b)$$

Micro-structure with statistic distribution of α- and β-phases

In such structures is a prediction of the critical J-integral of the compound (J_c^c) much more difficult. A simple determination of the fracture areas of α and β is no longer possible. Consider Figure 2. As indicated above, we assume that the crack will propagate preferentially through the phase with the lower toughness. Thus, the β-phase is fractured preferentially. If, however, the α-phase forms contiguous areas, then the α-phase too will be fractured for geometrical reasons (even if there is no contiguous area in a two-dimensional representation of the structure, e.g. a photo-micrograph, there may still exist a three-dimensionally contiguous α-phase). Thus, equation (1a) with $A_A^\alpha + A_A^\beta = 1$ may be written in the following form:

$$J_c^c = J_c^\alpha A_A^\alpha + J_c^\beta (1 - A_A^\alpha) \qquad (1b)$$

However, the equality $A_A^\alpha = V_V^\alpha$ is no longer valid. The contiguous volume fraction of α which is fractured for geometrical reasons is determined by the parameter "contiguity" for coarse two-phase structures with statistically distributed α- and β-phase.

The contiguity C is defined as the fraction of the total internal surface area of a phase that is shared by particles of the same phase (2). For instance for the α-phase in a α/β-compound

$$C^{\alpha} = \frac{2\, S_V^{\alpha\alpha}}{2S_V^{\alpha\alpha} + S_V^{\alpha\beta}}$$

where $S_V^{\alpha\alpha}$ is the shared boundary area between α grains and $S_V^{\alpha\beta}$ is the area of the interphase boundary between α and β per unit volume. The boundary areas can be measured by intercept counting along random lines on metallographic sections.

A structure model with connected α grains is shown in Figure 3. Let us consider the volume element i. The volume V_i of the element is given by

$$V_i^{\alpha} = a_i^{\alpha\alpha}\, l_i \cos \phi_i \qquad (4)$$

where $a_i^{\alpha\alpha}$ is the area of α grain - α grain contact, ϕ_i is the angle between the normal to the area a_i and the axis of the element i and l_i is the length of the element.

The volume V_{vc}^{α} of the connected portion per unit volume, after Lee and Gurland (3) also called contiguous volume, is the sum of the volumes of all elements i.

$$V_{vc}^{\alpha} = \frac{1}{V} \sum a_i^{\alpha\alpha}\, l_i \cos \phi_i = \frac{1}{2}\, \bar{l}\ \overline{\cos}\, \phi \frac{\sum 2a_i^{\alpha\alpha}}{V} \qquad (5a)$$

V is the total volume, $\bar{l}$ and $\overline{\cos}\,\phi$ are the average values of l_i and $\cos\phi_i$. For $\bar{l}$ we can substitute the linear mean intercept length $\bar{L}^{\alpha}$ (= grain size) and for $\cos\phi$ we can set 1/2 (4). So we get

$$V_{vc}^{\alpha} = \frac{\bar{L}^{\alpha}}{4V} \sum 2a_i^{\alpha\alpha} = \frac{S_V^{\alpha}\bar{L}^{\alpha}}{4} \frac{\sum 2a_i^{\alpha\alpha}}{S_V^{\alpha}\, V} \qquad (5b)$$

where S_V^{α} is the total surface area of the α grains per unit volume : $S_V^{\alpha} = 2S_V^{\alpha\alpha} + S_V^{\alpha\beta}$.

By using the Tomkeieff-equation

$$\bar{L}^{\alpha} = \frac{4\, V_V^{\alpha}}{S_V^{\alpha}}$$

and the relation

$$\frac{\sum a_i^{\alpha\alpha}}{V} = 2\, S_V^{\alpha\alpha}$$

the final result for the connected α-volume broken open by the crack is

$$V^{\alpha}_{vc} = C^{\alpha} V^{\alpha}_{v} \tag{5c}$$

Consequently the specific fracture area of the α-phase A^{α}_{A} is

$$A^{\alpha}_{A} = C^{\alpha} V^{\alpha}_{v}$$

Thus, with equation (1b), the fracture toughness of the compound can be described by a nonlinear rule of mixture

$$J^{c}_{c} = J^{\alpha}_{c} V^{\alpha}_{v} C^{\alpha} + J^{\beta}_{c} (1 - V^{\alpha}_{v} C^{\alpha}) \tag{6}$$

The fracture toughness of the alloy is thus determined by the fracture toughness of the phases involved and also by their volume fraction and by their contiguity. Only for the case of $C^{\alpha} = 1$ (a lumped α-phase) equation (6) is reduced to a linear rule of mixture. However, in real micro-structure $C^{\alpha} < 1$ and thus the toughness values J^{c}_{c} calculated according to equation (6) are always below the line of the linear rule of mixture (equation (2b)).

C^{α} decreases as the α grains are more and more separated by β grains. A micro-structure with isolated β islands in a α-matrix has a high α contiguity. A micro-structure with a β-network has a very low α-contiguity C^{α} . As expected by intuition, the network-microstructure will exhibit a smaller fracture toughness than the microstructure with β-islands and the same volume fraction of β.

SPECIFIC EXAMPLE: Al-Si-ALLOYS

We tested the fracture toughness of a number of modified Al-Si-alloys with different volume fractions of α-solid solution and eutectic. The test results are shown in Table 1. Fracture resistance curves J - Δa were measured with the single specimen-partially unloading-method. J_c was measured according to the proposed standard by the ASTM Task Group E24.01.09 (5).

TABLE 1 - Tested alloys

Alloy No.	%Si	V^{α}_{v}	C^{α}	J_c measured	J^{c}_{c} calculated
1	1,2	1,o	1,0	13,4-16,2	
2	4,0	0,76	0,34	7,0	5,8 - 7,6
3	7,0	0,57	0,21	5,2	4,4 - 6,0
4	10,0	0,37	0,145	4,6	3,8 - 5,2
5	14,0	0	0	3,2- 4,6	

Table 1 contains also the fracture toughness calculated according to equation (6).

The results are graphically shown in Figure 4. The ductile phase is a α-solid solution ($V_v^\alpha = 1$) with a J_c^α of 13,4 - 16,2 kJ/m^2. The brittle phase is the eutectic ($V_v^\alpha = 0$) with J_c^β of 3,2 - 4,6 kJ/m^2.

For the α-β structure ($0 < V_v^\alpha < 1$), equation (6) gives the scatterband shown in Figure 4. The experimentally determined toughness values J_c^c are without exception inside this scatterband thus nicely confirming the rule of mixture given by equation (6).

It is remarkable that the toughness values J_c^c of the two-phase alloys are always significantly below the linear rule of mixture, as indicated in Figure 4. The eutectic forms a continuous network even if its volume content V_v^β is small. The contiguity of the α-lines is correspondingly small. Thus a crack propagates mostly through the eutectic, even if the volume fraction of the eutectic is comparatively small.

SYMBOLS USED

α = symbol for the ductile phase

β = symbol for the brittle phase

A_A^α = specific fracture area of the α phase

A_A^β = specific fracture area of the β phase

C^α = contiguity of the α-phase

J_c^α = critical J-Integral of the α phase (kJ/m^2)

J_c^β = critical J-Integral of the β phase (kJ/m^2)

J_c^c = critical J-Integral of the compound (kJ/m^2)

S_v^α = total surface area of the α grains per unit volume

$S_v^{\alpha\alpha}$ = shared boundary area between α grains

$S_v^{\alpha\beta}$ = shared interphase boundary area between α and β grains

V_v^α = volume fraction of the α phase

V_v^β = volume fraction of the β phase

V_{vc}^α = contiguous volume of the α phase

REFERENCES

1. Merkle, J.G., and Corten, H.T., 1974, J. of Press Vessel Techn., 9, 286

2. Underwood, E.E., 1969, Quantitative Stereology, Addison-Wesley, Reading, Mass.

3. Lee, H.C., and Gurland, J., 1978, Mat. Sci. Eng., 33, 125

4. Exner, H.E., and Hougardy, H.P., Quantitative Analyse, DGM, Oberursel

5. Clarke, G.A., Andrews, W.R., Begley, J.A., Donald, J.K., Embley, G.T., Landes, J.D., McCabe, D.E., and Underwood, J.H., 1979, J.of Testing and Evaluation, 7, 49

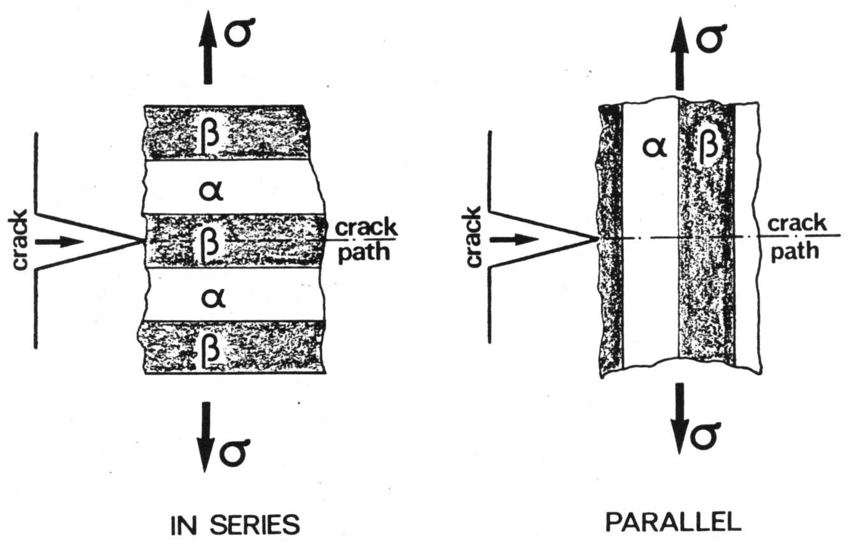

Figure 1 In series and parallel compound of a two-phase structure

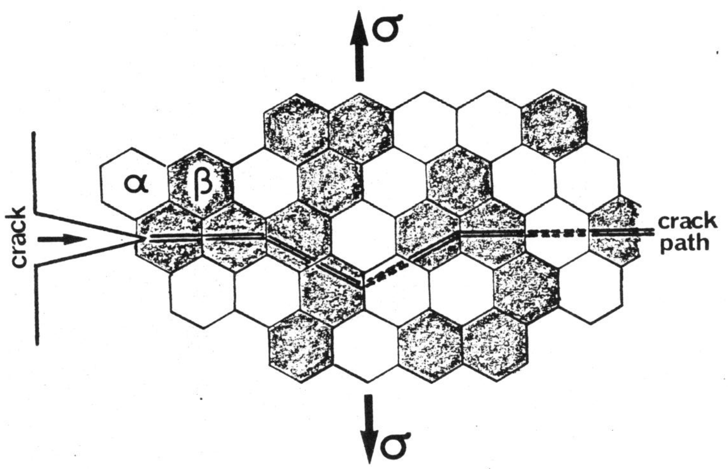

Figure 2 Two-phase structure with a statistical distribution of α and β-grains

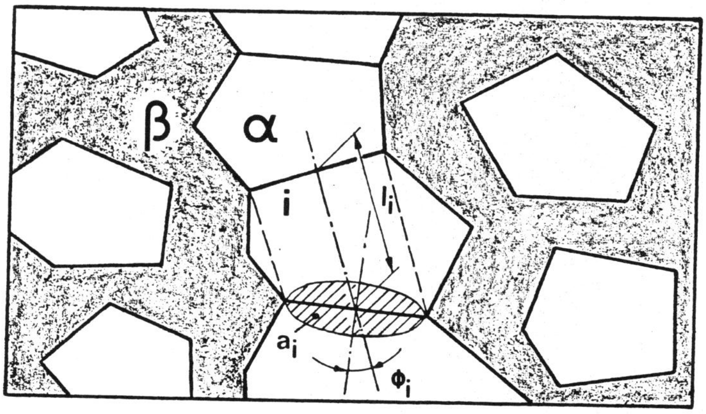

Figure 3 Structure model for the calculation of contiguous volume

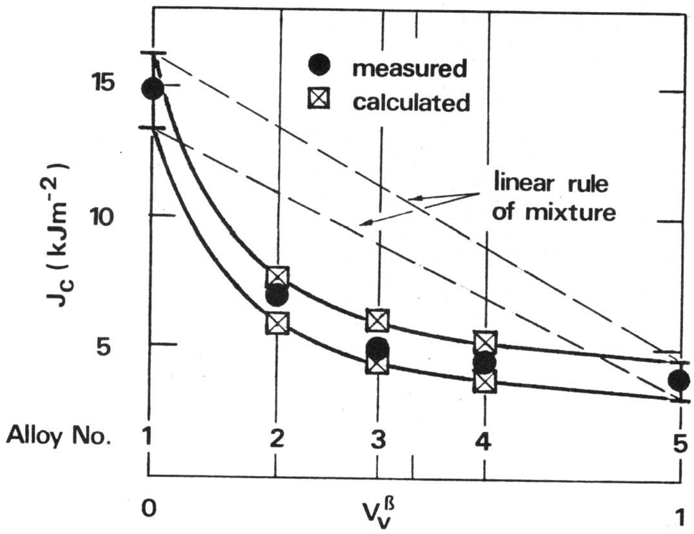

Figure 4 Calculated and measured J_c-values of the Al-Si-alloys