The Influence of Fibre - Matrix Reactions on the Fracture of Composites with Aluminium and Nickel as Matrix Materials

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In fibre-reinforced composites diffusion processes at the boundary surface between fibre and matrix may occur at considerable rates if the material is subjected to elevated temperatures.

In the case of metal matrix/metal fibre systems the following mechanisms have to be taken into account:

1. The formation of solid solutions which may proceed to the point of complete dissolution of the fibres in the matrix material.
2. Solid state reactions resulting in the formation of intermetallic phases.

These processes will change the mechanical properties and the fracture behaviour of the composite materials. Detrimental effects due to these processes may be:

1. Embrittlement of the components, which in case of unfavourable shapes produced by the growth of the layers formed by means of the diffusion process may lead to premature failure of the material (notch effect).
2. The formation of pores, which occurs if the diffusion coefficients of the atoms constituting the components differ markedly. These pores will not only reduce the

load bearing cross section, they will also act as stress concentrating flaws.

3. Deterioration of the bond between fibre and matrix or even delamination of the components, if a volume concentraction occurs as a result of the solid state reaction.

In the three cases mentioned above the conditions necessary for an effective utilization of the principle of fibre reinforcement are not fulfilled any longer. On the other hand, however, it is possible by selecting suitable fibre-matrix combinations and appropriate diffusion heat treatment to produce composite materials with interfacial layers providing an improved transfer of stress between fibre and matrix. As the interfacial layers produced by means of heat treatment are of higher thermal stability they may, in addition, serve for the protection of the fibres at elevated temperatures. The thermodynamically most stable composite is obtained, if the fibres are completely transformed into the phase which corresponds to the state of equilibrium in the temperature range under consideration.

The investigations have been carried out on composite materials produced by means of liquid infiltration. The different fibre-matrix combinations investigated, the temperature of heat treatment in each case, the reaction products, and their morphology are given in table 1.

In combination I (aluminium/pure iron wire) a diffusion layer consisting of Fe_2Al_5 is produced which grows into the iron wire in a quite irregular shape because of its anisotropy of growth due to the crystallographic structure of the Fe_2Al_5 phase. From the results of the tensile tests it may be assumed that the irregularities of the growth front lead to a decrease in strength of the composite. The relatively high inherent strength of the intermetallic phase cannot be utilized since brittle fracture occurs at quite

low loads in the Fe_2Al_5 phase because of stress concentration at the notches.

This irregularity in growth and shape of the intermetallic phase is not observed if high alloy steel wire (AISI 302, DIN 4300) is used instead of the iron wire (combination II). This is due to the presence of the alloying additions which serve to impede the diffusion process. In the case of combination II a uniform layer of the transformation product is observed, which does not show delamination at the fibre-matrix interface. Within the diffusion layer,which again consists mainly of Fe_2Al_5, however, a seam of pores is formed which, in turn, weakens the composite. Scanning electron micrographs of the fracture surface indicate that fracture is initiated at these pores.

In combination III (aluminium/nickel wire) the intermetallic phases Ni_2Al_3 and $NiAl_3$ are formed during heat treatment of the composites, where $NiAl_3$ is the thermically more stable phase. Composites thus treated show an increase in tensile strength over that of the matrix. This increase in strength is considerably higher for elevated temperatures than for room temperature. Examination of the fracture surfaces showed that at room temperature fracture occurs at grain boundaries in both intermetallic phases. Macroscopically the fracture surface resembles that of a normal-stress fracture. At temperatures in excess of 300°C a tendency towards a shear-type fracture is observed.

In all three combinations described above the aluminium matrix shows ductile fracture with narrow ridges in the immediate vicinity of the fibres and dimpled fracture in the remaining spaces. The necking of the matrix leads to delamination of fibre and matrix in the region of the necked fracture surface for the last phase of the fractoring process.

In combination IV (nickel/tungsten wire) a nickel-tungsten solid solution is produced by heat treatment above 1000°C. Due to the much higher rate of diffusion of the nickel atoms during the formation of the solid solution a quite marked seam of pores is produced in the nickel matrix. The diffusion processes cause, as scanning electron micrographs show, a very strong bond between fibre and matrix. The cohesive strength between nickel-tungsten solid solution and remaining tungsten wire is higher than the fracture strength of the tungsten. This is seen from the fact that tungsten particles are torn out of the remaining tungsten fibre material. The pores, however, cause a decrease in strength of the composite material.

By adding carbon to the nickel matrix and subjecting this composite material (combination V) to a suitable heat treatment it is possible to produce carbide layers on the fibre surfaces which act against the formation of a solid solution. They prevent the formation of pores and the dissolution of the fibres. The bond between matrix and carbide layer is enhanced by the volume expansion of the reaction product. Examination of the fracture surface confirms that the bond at the boundary surfaces remains intact in the moment of fracture. The brittle carbide phase fails by cleavage in a plane perpendicular to the direction of the applied force. At temperatures beyond 700°C radial cracks parallel to the fibre axis are observed in the carbide phase. The occurrence of which may be explained with a tri-axial state of stress and the anisotropy of growth of the carbide phase.

Combination	Matrix	Fibre	Temperature of heat treatment [°C]	Reaction products	Morphology
I	Al	Fe	600	Fe_2Al_5	irregular shape of diffusion layer
II	Al	steel wire (AISI302)	600	Fe_2Al_5	regular shape of diffusion layer, seam of pores in the Fe_2Al_5 phase
III	Al	Ni	600	Ni_2Al_3/$NiAl_3$	regular, concentric diffusion layers
IV	Ni	W	1000 - 1350	Ni-W solid solution	seam of pores in the matrix surrounding the fibres
V	Ni-C alloy	W	1060	W carbides Ni-W carbides	regular shape of diffusion layer with serrated inner front

Table 1: Survey of the composites investigated