7. T. TAKENAKA, M. TAKIGAWA and K. SHOHNO, *Jap. J. Appl. Phys.* 14 (1975) 579.
8. Y. HIRAI and K. SHOHNO, *J. Crystal Growth* 41 (1977) 124.
9. J. LINDSTROM, K. FUNDELL and A. LIND, in "Chemical Vapour Deposition, 4th International Conference" (Electrochemical Soc. Inc, Princeton, (1973) p.546.
10. S. WAKAMATSU, *Bunseki Kagaku* 9 (1960) 22.

Received 25 May
and accepted 19 July 1978.

SEIJI MOTOJIMA
YOSHINORI OHTSUKA
SHOHGO KAWAJIRI
YASUTAKA TAKAHASHI
KOHZO SUGIYAMA
Department of Synthetic Chemistry,
Faculty of Engineering,
Gifu University, Kakamigahara,
Gifu 504,
Japan

Quenching efficiency of some splat-cooling devices

The purpose of this communication is to summarize certain observations concerning the efficiency of quenching from the liquid state (splat-cooling) by four rapid cooling devices. These were designated according to the following, now widely used terminology: the "gun", the "two-piston", the "mill" and the "levitation" methods.

In the "gun" method a liquid drop is projected at high speed on to a copper substrate. An apparatus similar to the type designed by Duwez *et al.* [1], but with the copper target cooled with liquid nitrogen, was used.

In the "two-piston" method [2] a liquid globule is squeezed between two metallic flat surfaces activated by a high gas pressure. Pistons made of steel were used.

In the "mill" method [3] a molten alloy is injected between two counter-rotating brass cylinders with a hard chrome surface.

The "levitation" method [4] combines the advantages of melting without the use of a crucible with the "two-piston" technique [5, 6]. Our design [7] included both copper and hard-metal pistons.

As a test for the efficiency of quenching by splat-cooling devices the Ag–Cu system was used. The equilibrium diagram of this binary alloy exhibits a eutectic, although the Hume–Rothery conditions are satisfied. However, Duwez demonstrated [8] that in this binary alloy fast quenching from the melt, if efficacious, results in complete solubility. Depending on the cooling rate during quenching, different phases can be obtained. With optimum conditions, a single-phase, metastable fcc random solid solution will result over the entire Ag–Cu composition. This solid solution exhibits a slight, positive (~1%) deviation from Vegard's law and has been termed γ' [9]. Under less efficient quenching, a metastable fcc structure, marked by a ~3% deviation from Vegard's law, may occur. It was termed γ'' by Stoering and Conrad [10]. Deviating farther from γ', silver-rich and copper-rich metastable fcc solid solution phases may occur. These have been termed α' and β' to distinguish them from the equilibrium phases α (Ag-rich) and β (Cu-rich) [9]. A decrease in the cooling rate during quenching produces phases which depart from the ideal solid solutions given by Vegard's law. Thus the Ag–Cu system appears very convenient for testing the efficiency of splat-cooling.

Alloys were made using Ag and Cu of purity $\geqslant$99.99 wt%. The components were weighed accurately to 0.1 mg. Initial melts were made in a graphite crucible under an argon atmosphere using induction heating. In the "gun", "two-piston" and "mill" methods samples in form of strips, weighing 150 to 200 mg, and in the levitation method samples of prismatic form, weighing 200 to 300 mg, were used.

Flakes quenched rapidly by the "gun" method were about 1 cm wide and 2 to 3 cm long and contained a large number of holes. As a result their thickness varied by up to 20 μm. The quenched flakes resulting from the "two-piston" method were approximately circular, about 1 to 5 mm in diameter, and 10 to 20 μm in thickness. In the "mill" method, the parameters were adjusted in order to obtain samples in the form of

TABLE I Lattice parameter measurements (in Å) on liquid-quenched Ag–Cu alloys for different silver concentrations. Observed diffraction lines, whose exact position was impossible to measure because of their weak intensity and broadness, are indicated by*.

Quenching method	Phase	Concentration (at % Ag)			
		11.5	37.1	60.1	69.3
Gun	α'		*		
	γ'	3.694	3.852	3.943	3.965
	β'				
Two-pistons	α'	4.083	4.031	4.029	4.035
	γ'	3.690	3.871	3.938	
	β'	3.651	3.662	3.650	3.660
Mill	α'		*		
	γ'	3.700	3.860	3.946	3.960
	β'	3.669	*		
Levitation	α'	4.036	4.030	4.034	4.026
	γ'			3.939	3.961
	β'	3.666	3.650	*	

strips about 2 to 3 cm long, 1 to 2 mm wide and 10 to 20 μm thick. In the "levitation" method, the thickness of the quenched foils varied from 50 to 100 μm and were approximately circular, 2 to 3 cm in diameter.

The quenched samples were placed into 0.5 mm glass capillary tubes and examined in a 114.6 mm diameter Debye–Scherrer camera with nickel-filtered CuK radiation. The films were corrected for shrinkage, and the lattice parameters determined by extrapolation against the Nelson–Riley function. The results are presented in Table I. The lattice parameters of the phases designated as α', β', γ' and γ'' are plotted in Fig. 1 against the composition for the specimens quenched from temperature between 1200 and 1300° C. In the same diagram, the results for γ' obtained by Duwez *et al.* and Linde [8, 11], and γ'' by Stoering and Conrad [10] are plotted.

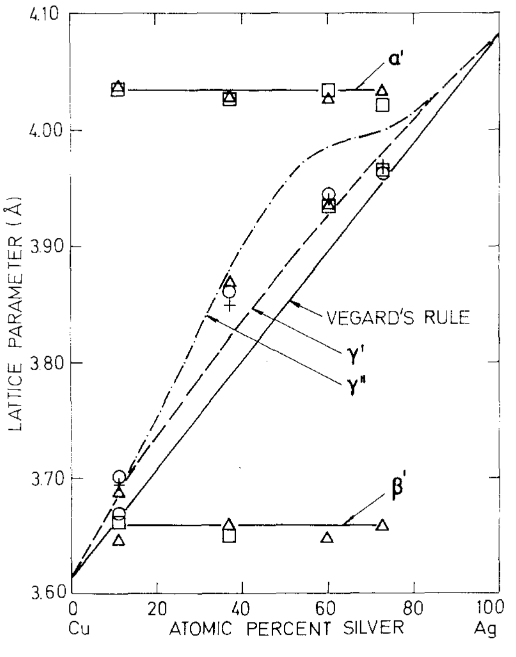

Figure 1 Lattice parameters of the phases α', β', γ' and γ'' against the composition for the splat-cooled specimens. + – gun; △ – two-pistons; ○ – mill; □ – levitation, — — — γ', Duwez *et. al.* [8] and Linde [11]. — · — · γ'', Stoering and Conrad [10].

Using the "gun" quenching method γ' phase was obtained for all concentrations, while at the concentration 37.1 at % Ag, weak lines of the metastable α' phase appeared as well. When the copper target was cooled with liquid nitrogen, the same result was obtained as at room temperature.

Using the "two-piston" method, the γ' phase was accompanied by α' and β' phases, whose lattice parameters were in reasonable accordance with earlier results [9, 10]. Only at a concentration of 69.3 at % Ag was the γ' phase not present in any sample.

Using the "mill" method γ' was obtained for all concentrations. At 11.5 at % Ag, metastable β' phase appeared simultaneously, and at 37.1 at % Ag traces of α' and β' appeared. However, their lines were so weak that it was impossible to measure the lattice parameters, and so they are not presented in Fig. 1.

Using the "levitation" method, alloys were quenched between both copper and hard-metal pistons. The γ' phase was obtained only at two concentrations, simultaneously with α' and traces of β' phases, but only when copper pistons were used. At two other concentrations α' and β' were present.

As regards efficiency of quenching our experiments allow us to range the four splat-cooling devices in the following order:

(1) "Gun" technique (9.5×10^7 K sec^{-1})
(2) "Mill" technique (5.0×10^7 K sec^{-1})
(3) "Two-piston" technique (5.0×10^7 K sec^{-1})
(4) "Levitation" technique with copper pistons (1.3×10^7 K sec^{-1})
(5) "Levitation" technique with hard-metal pistons (3.1×10^6 K sec^{-1}). In brackets are given the rates of cooling calculated using approximations similar to those used by Blétry [12].

In comparing the efficiency of quenching we should not forget that in special cases certain methods of splat-quenching are more convenient, e.g. the levitation method for obtaining samples of high purity; hard-metal pistons for quenching alloys with a high melting point, and the "gun" method produces samples which are very suitable for transmission electron microscopy investigation. In all these cases quenching efficiency may not be the most important quality of the device.

References

1. P. DUWEZ and R. H. WILLENS, *Trans. AIME* **227** (1963) 362.
2. P. PIETROKOVSKY, *Rev. Sci. Instrum.* **34** (1963) 445.
3. E. BABIĆ, E. GIRT, R. KRSNIK, B. LEONTIĆ and I. ZORIĆ, *Fizika* **2** (Suppl. 2) (1970) 2.1.
4. W. A. PEIFER, *J. Met.* **17** (1965) 487.
5. P. ESSLINGER and W. WOLF, *Zeit, Wirt. Fert.* **60** (1965) 449.
6. R. W. CAHN, K. D. KRISHANANAND, M. LARIDJANI, M. GREENHOLTZ and R. W. HILL, *Mater. Sci. Eng.* **23** (1976) 83.
7. O. MILAT, D. DUŽEVIĆ and A. BONEFAČIĆ, *Fizika* 8 (1976) 25.
8. P. DUWEZ, R. H. WILLENS and W. KLEMENT Jr., *J. Appl. Phys.* **31** (1960) 1136.
9. S. NAGAKURA, S. TOYAMA and S. OKETANI, *Acta Met.* **14** (1966) 73.
10. R. STOERING and H. CONRAD, *ibid.* **17** (1969) 933.
11. R. K. LINDE, *J. Appl. Phys.* **37** (1966) 934.
12. J. BLETRY, *J. Phys. D: Appl. Phys* **6** (1973) 256.

*Received 22 May
and accepted 8 June 1978.*

V. FRANETOVIĆ
O. MILAT
D. IVČEK
A. BONEFAČIĆ

*Institute of Physics of the University,
Bijenička c. 46, 41001 Zagreb,
Yugoslavia*

Failure analysis of unidirectional glass-reinforced brittle matrix composites by the fault tree technique

In a recent paper by Masters *et al.* [1], a fault tree technique was used in a qualitative way for the identification of failure mechanisms occurring in laminated composite materials. That analysis reflects the fact that in composites there is a wide variety of overlapping fracture micromechanisms whose individual contributions are often shielded by the complexity of the general fracture process. The fault tree technique is applied in order to divide the general fracture process into chains of basic independent events to which a related probability of occurrence is theoretically assigned. This analysis is a bridge between a macroscopic physical event (the failure of the material) and its microscopic origins, and is used qualitatively to examine the static tensile failure of a fibrous composite laminate.

The present paper proposes a quantitative fault tree for failure of unidirectional glass fibre-reinforced brittle matrix composites, and it is a particular case of the general fault tree presented in [1]. The fault tree proposed here assigns a theoretical expression for the energy absorbed at each step of the chains of basic events, and an expression for the relative probability of occurrence of the two chains. Moreover, two fundamental parameters are underlined in our analysis: the interface strength (τ_i); and the fibre condition, that is, whether or not weak points are present in the fibre. Piggott, in a previous work [2], has