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Instrumented dart impact evaluation of composite laminates for printed circuit board applications

E. L. RODRIGUEZ
B. F. Goodrich Company, Avon Lake Technical Center, Avon Lake, Ohio 44012, USA

Double-sided copper film and single-sided copper film epoxy/glass fabric laminate for printed circuit board applications were examined for impact strength at different velocities of deformation and different temperatures. An instrumented dart impact tester was employed in the experiments. The single-sided copper laminates were evaluated by first placing the copper film face up facing the impacter, and second by placing the copper film face down away from the dart. It was found that the maximum force of deformation was almost independent of the initial velocity of deformation, and the total energy was found to increase with velocity. In addition, the maximum force and the total energy were found to decrease linearly with temperature for every case. A brittle feature was also prevalent in the damaged composite. A cross-type of fracture was also common where more damage was found with increasing velocity of impact. A combination of brittle failure with fibre pullout, as well as a brittle failure with debonding or matrix failure were also found by examining the fracture surfaces with a scanning electron microscope.

1. Introduction

Organic matrix composite laminates for printed circuit boards are extensively used in the electronic industry. The most common electric laminates are usually made by the pre-preg process where the glass fabric is impregnated in a resin bath, squeezed by rolls, and then passed through one or more heating zones. In the heaters, the laminate is first stripped of solvents and other volatiles and then the resin is advanced to the B-stage to result in a material which is relatively dry and slightly tacky [1, 2]. The temperature, speed of travel, resin content, and resin type will have an effect on the degree of B-staging. This process is used for laminates to be cured at high temperatures or by ultraviolet radiation.

To prepare the laminate, one or several layers of the B-stage material is placed between one or two layers of copper foil. The stacked composite is then placed in the heated press and consolidated under the influence of heat and pressure into one multi-ply laminate.

The circuit is printed on the foil in acid-resistant material and the excess copper etched off, leaving the conductive path exposed on a rigid sheet material. Holes are then punched in the sheet for fixing components such as transistors or resistors, which are soldered in place.

The printed circuit board serves both a mechanical and an electrical function. Mechanically, it must have sufficient strength to support the components and withstand a certain level of impact without fracturing. Electrically, the board must have sufficient dielectric strength, which is the maximum voltage that a material can withstand without allowing a current to pass.

Prior to service, the boards or laminates are usually exposed to chemical treatments (acid etching, cleaning, soldering agents) and mechanical stresses (drilling). It is proposed that impact studies can be used to characterize and to follow how the different chemical and mechanical treatments affect the mechanical integrity of the laminates.

The impact behaviour of polymeric and composite materials has always been a difficult area of research mainly due to the lack of satisfactory test techniques. The instrumented pendulum and falling weight impact techniques are growing in use because more information is obtained concerning the fracture process than in a conventional non-instrumented impact test. Some thermoplastics [3–7], thermosets [8, 9] and composite materials [10–18] have been examined using the instrumented impact techniques. Furthermore, instrumented impact tests on plastics and composites are becoming more popular because of the availability of commercial equipment and because of the need to obtain more information on the fracture process under impact conditions.

In this report, an instrumented puncture tester is used to evaluate copper-clad laminates for circuit board applications. Emphasis is given to the effect of the construction of the copper-clad laminates on the impact parameters. No discussion is presented concerning the instrumentation because considerable progress has been made in the electronic and data analysis [19]. The impact event is examined

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TABLE I Typical epoxy matrix formulation for an electric laminating resin

Formulation 1	
Dow Epoxy Resin DER-521-70	100 parts
Dow Epoxy Resin DER-661-30	
(Brominated and unbrominated epoxy resin)	
Dicyandiamide (cure agent)	3 parts
Benzyldimethylamine (cure accelerator)	0.25 parts
Solvent	Mixture of methyl cellosolve/acetone
Cure time	120 min at 177° C
Formulation 2	
Dow Epoxy Quatrex 5010	
Nonvolatiles	75%
Solvent type	methyl ethyl ketone
Bromine content	30% to 32%
Cure time	90 min at 177° C

by following the amount of load required to break the specimens, the impact energy and the displacement during the impact process.

2. Experimental procedure

One-sided and two-sided copper-clad laminates were kindly supplied by the General Electric Company, Electromaterials Group Coshocton, Ohio. The resin, glass fabric, composition and the cure process are proprietary information and were not released for the materials description. However, Table I shows two typical formulations for a standard epoxy laminating resin, the most common resin used in printed circuit boards [20–22]. Dow epoxy resin Quatrex 5010 is a new one-component resin system for high-performance PC board. The general chemistry and cure of epoxy resin for printed circuit board application can be found, for example, in [1].

An instrumented puncture impact tester, Rheometrics RDT-5000 with an automatic plaques loader, was used to evaluate the impact strength of the laminates. Samples were cut to $6.35 \times 6.35\,\text{cm}^2$ ($2.5 \times 2.5\,\text{in}^2$) dimensions. The average thickness of the laminate was 1.575 mm (0.0620 in). The thickness of the copper foil in the laminates was approximately $80\,\mu$m. An average of five specimens was tested for each condition.

The high-energy dart of 10.4 kg (23 lb) in weight, a probe impacter of 1.27 cm (0.5 in) diameter, and a retainer clamp ring of 2.54 cm (1 in) diameter were employed. Fig. 1 describes the test configuration. The clamping pressure on the specimen was approximately $6.90\,\text{MN}\,\text{m}^{-2}$ (1000 p.s.i.). For the subambient temperature, samples were allowed to equilibrate for 3 h prior to testing. The automatic sample loader in the Rheometrics RDT-5000 unit is a combination of a carousel where 50 specimens can be placed at one time and a delivery arm that automatically grabs the sample from the environmental chamber to the testing unit. This unique feature allows us to test large numbers of specimens in a considerably shorter period of time.

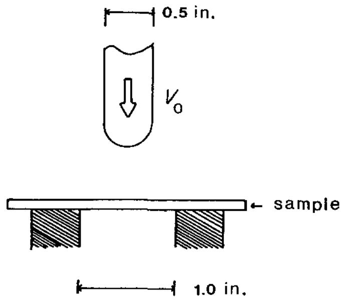


Figure 1 Test configuration in the drop dart test.

Thermogravimetric analysis was employed to determine the resin content, and a dynamic mechanical analysis in the resonant mode was conducted to determine the glass transition of the epoxy resin. The Dupont 1090 system with the TGA and DMA 982 modes were employed.

The conversion factors used in this report are 1 J = 8.8512 in lb for energy, and 1 N = 0.2248 lb for force.

3. Results and discussion

The one-sided copper film laminate was evaluated in two ways to determine how the orientation of the copper film, with respect to the impacter, affected the impact strength. First, the copper foil faced the dart and the impact event took place on it. Second, the copper foil was away from the dart and the impact event took place on the glass fabric/epoxy side. The one-sided and double-sided copper laminates were evaluated under similar conditions.

In the Rheometrics RDT-5000 unit, the velocity

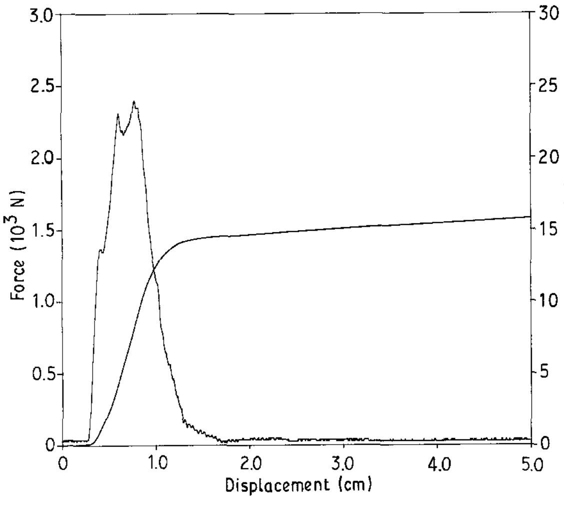


Figure 2 A typical force-displacement/energy curve for the two-sided copper film.

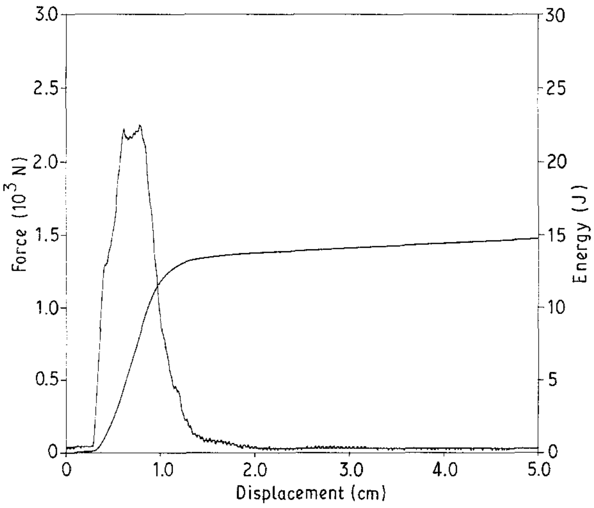


Figure 3 A typical force–displacement/energy curve for the one-sided copper film; copper film side up, facing the dart.

and load transducers on the probe record complete load–deflection and energy–deflection traces during the impact event. The yield deflection, yield energy, ultimate force, and total energy can be obtained from the plotted traces.

Figs 2 to 4 show a typical force–displacement/energy graphs for the two-sided copper film, for the one-sided copper film (copper film side up), and for the one-sided copper film (copper film side down) for the initial velocity of deformation of $3.12\,\mathrm{m\,sec^{-1}}$ ($123\,\mathrm{in\,sec^{-1}}$) and at 21° C, respectively.

The force–deflection curves give considerable information with respect to the impact event. Knakal and Ireland [23] suggested that the relative shape of the load–deflection record is indicative of the deformation and fracture history of the material. Thus, the concepts used in the interpretation of the load–deflection curve in a typical tensile test can be applied to a puncture impact test with the important observation that the dart test imposes a biaxial flexural deformation to the specimen.

In this report, the maximum force, (F_{max}), which is an indication of the biaxial flexural strength, and the total impact energy, E_{T}, which is indicative of biaxial flexural impact toughness, were chosen to characterize the impact performance of the copper-clad composite laminates.

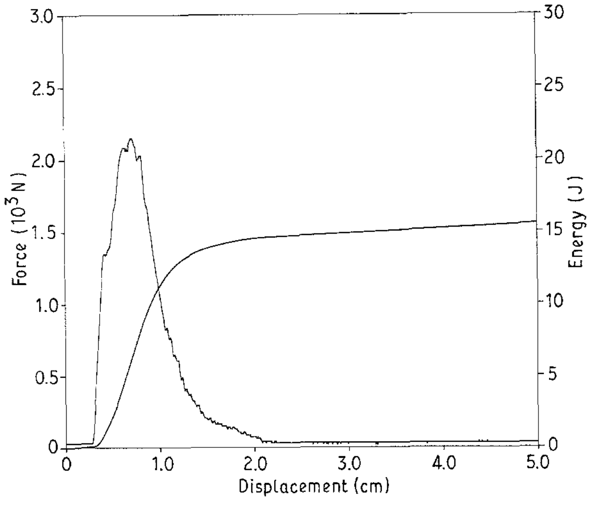


Figure 4 A typical force–displacement/energy curve for the one-sided copper film; copper film side down, away from the dart.

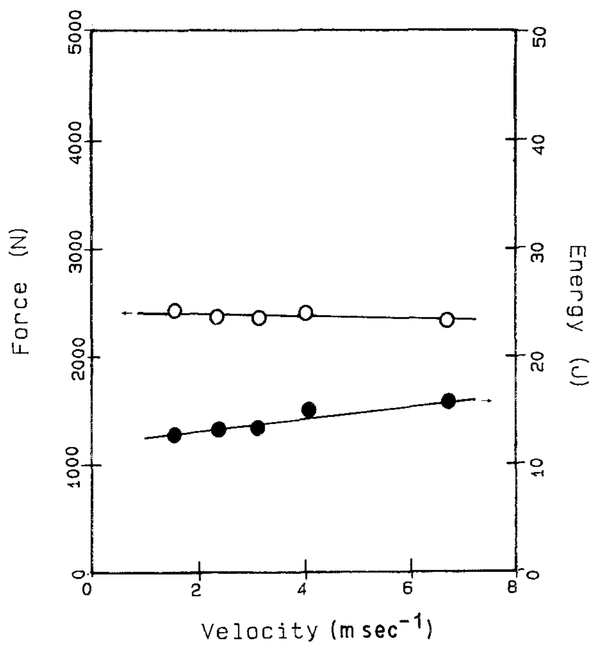


Figure 5 (○) Maximum force and (●) total energy dependence on initial velocity of deformation for the two-sided copper laminate at 21° C.

In impact research, the test temperature and the rate of deformation are two important variables (among others) that will influence the impact parameters and the fracture characteristics of plastic materials [24]. In this report, our interest was to examine how these two variables affect the puncture impact properties of copper-clad composite laminates. Thus, the initial impact velocity was varied from 0.5 to $8.0\,\mathrm{m\,sec^{-1}}$ and the test temperature from − 60 to 120° C. Fig. 5 shows the maximum force and the total energy dependence for the two-sided copper layer laminate at 21° C. The maximum force was found to be almost independent of velocity, and the total energy showed a slight increase with velocity. Fig. 6 shows the puncture impact data as a function of temperature at constant initial velocity of $3.12\,\mathrm{m\,sec^{-1}}$ ($123\,\mathrm{in\,sec^{-1}}$) for the two-sided copper laminate. In this case, both the maximum force and the total energy decreased linearly with temperature.

Fig. 7 shows the impact results for the one-sided copper laminate, copper film facing the dart, at different initial velocities of deformation at 21° C. The maximum force was almost independent of the initial velocity, and the total energy slightly increased with velocity. Fig. 8 shows the impact data as a function of temperature at constant velocity of $3.12\,\mathrm{m\,sec^{-1}}$ ($123\,\mathrm{in\,sec^{-1}}$) at 21° C where, again, both the maximum force and total energy decreased with temperature.

Fig. 9 shows the maximum force and total energy dependence on the velocity of deformation for the one-sided copper layer laminate, copper film face down away from the dart. Here again, the maximum force was found to be independent of velocity and the total energy showed a slight increase with the initial velocity of deformation.

Fig. 10 shows the maximum force and the total

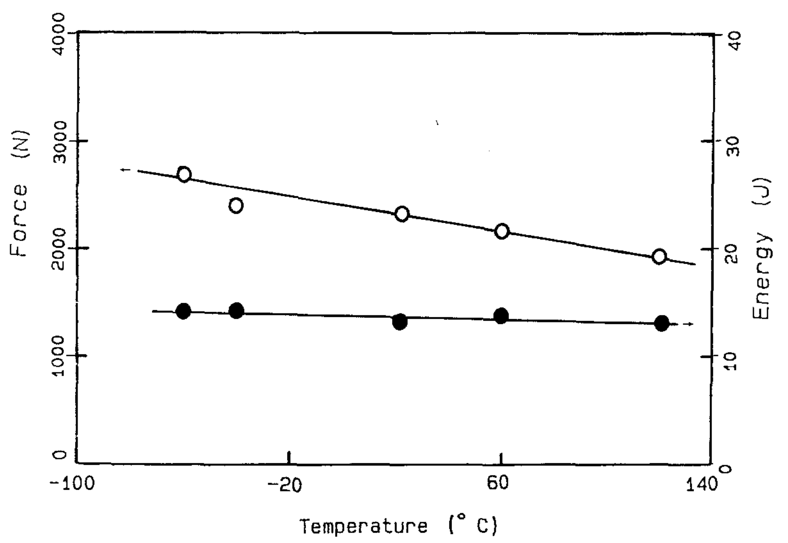


Figure 6 (○) Maximum force and (●) total energy dependence on temperature for the two-sided copper laminate at the initial velocity of deformation 123 in sec^{-1}.

energy decrease with temperature at constant velocity of 3.12 m sec^{-1} (123 in sec^{-1}).

It is interesting to note that for the three laminates examined, the total energy and maximum force dependence on temperature and velocity followed similar trends. For the velocity characterization, the puncture strength was nearly independent of rate, and the puncture impact energy showed a small increase with rate of deformation (Figs 2, 5 and 9). For the temperature characterization, both the puncture strength and toughness showed a slight decrease with temperature (Figs 6, 8 and 10).

This behaviour is very common in brittle materials [24]. Vicent [25] has shown that the brittle strength, σ_b, for polymethylmethacrylate (a brittle thermoplastic) slightly increased with strain rate and slightly decreased with temperature. This general trend in brittle material agreed with our results for composite copper-clad laminates. This supports the general observations made by Vicent [25] concerning the effect of strain rate and temperature on the failure of diverse plastics.

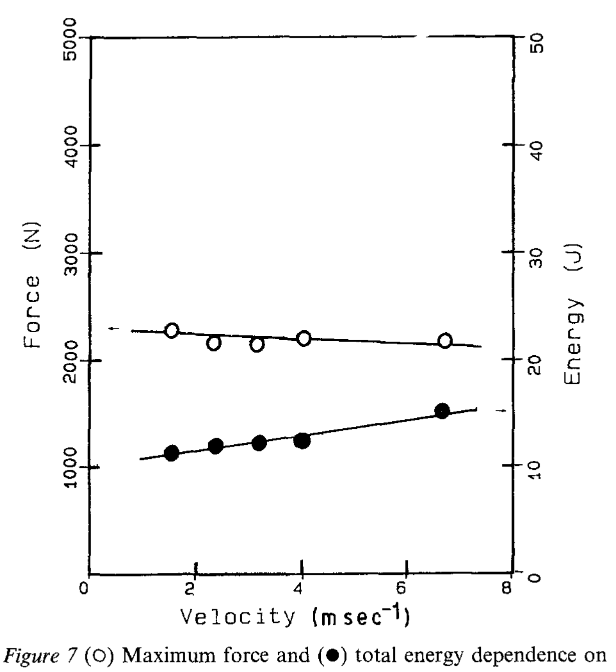


Figure 7 (○) Maximum force and (●) total energy dependence on initial velocity of deformation for the single-sided copper laminate, copper film face up, at 21° C.

Examining the effect of the copper layers, the two-sided copper laminates showed a slightly higher maximum force and total energy than the one-sided copper laminates. For example, for 3.12 m sec^{-1} (123 in sec^{-1}) rate of deformation and at 21° C, laminate 1 showed F_{max} = 2362 N and E_T = 13.3 J, laminate 2 showed F_{max} = 2157 N and E_T = 12.3 J and laminate 3 showed F_{max} = 2151 N and E_T = 12.0 J, for the two-sided copper layer laminate, the one-sided copper layer laminate with copper film facing the dart, and the one-sided copper layer laminate with the copper film away from the dart, respectively. These differences were more accentuated at different velocities and test temperatures. The maximum force (puncture strength) showed more pronounced differences between the composite laminates than the total impact energy (toughness) values. In general, for the one-sided copper laminates, the maximum impact force and the total energy were higher for the case where the impact event took place on the copper film, that is, the copper film facing the impacter.

Thus, the results showed that the presence of copper film in both sides of the laminate improved the strength of the composite. For a single-sided copper laminate, a slightly higher impact strength was found when the impacter hit the metallic film. This is related to the high impact energy absorbance capabilities of the copper film.

The impact strength in a glass fabric/epoxy laminate is known to be a function of the resin content. The most common resin content for printed circuit laminates is about 35% to 40%. A thermogravimetric analysis showed a glass resin content of approximately 38% by weight. It was assumed that the laminates had similar resin content as was described by the supplier. Fig. 11 shows the weight loss % as a function of temperature of the double-sided laminate. The dynamic mechanical analysis was conducted to determine the glass transition of the epoxy matrix and to examine any secondary relaxation. No secondary transitions were found, as is illustrated in Fig. 12. The glass transition of the epoxy resin matrix was approximately 170° C, as determined from the maximum tan delta.

The decrease of the maximum force and total

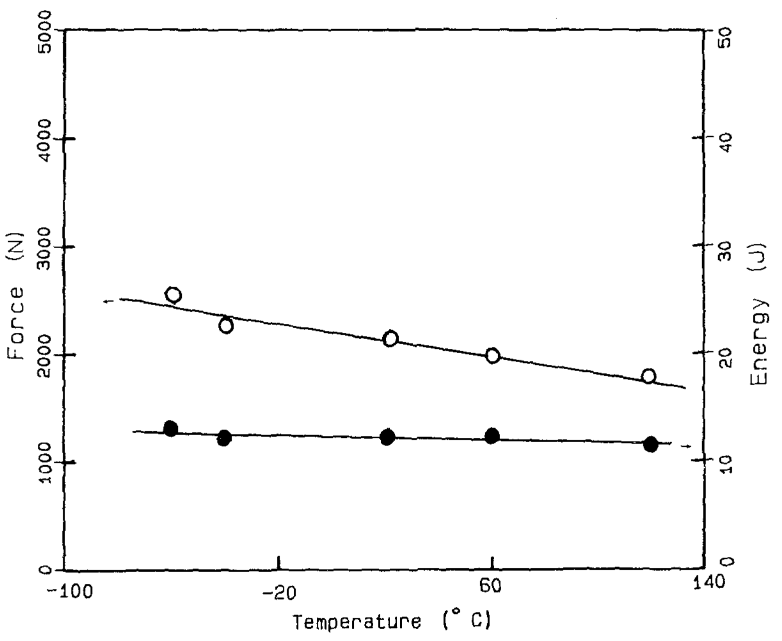


Figure 8 (○) Maximum force and (●) total energy dependence on temperature for the single-sided copper laminate, copper film face up, at 123 in sec^{-1}.

energy for the three composite laminates with temperature are related to the decrease in the stiffness (or elastic modulus) of the epoxy resin with temperature. This can be seen from the slight decrease in the dynamic storage modulus, E', with temperature (Fig. 12). In the dynamic test, the storage modulus reflects the elastic response of the material to an applied strain. Thus, the loss in impact properties with temperature may be explained from the loss in the dynamic storage modulus with temperature.

Tables II and III show the results of the curve fitting analysis for the maximum force and total energy dependence on temperature. A linear fit was found to describe their temperature dependence. The slope b (N °C^{-1} for force and J °C^{-1} for energy) were found to be higher for the single-sided copper laminates than for the double-sided copper laminates. This indicates that the presence of the copper films in the composite improves their strength with temperature.

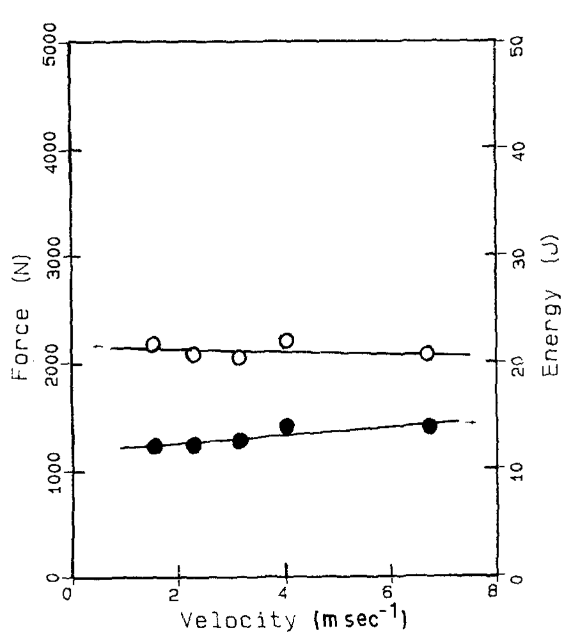


Figure 9 (○) Maximum force and (●) total energy dependence on initial velocity of deformation for the single-sided copper film laminate, copper film face down, at 21° C.

In the construction of printed circuit boards, the type and nature of the fabric plays an important role in the overall properties of the laminates. A glass fabric with a plain weave is common in printed circuit board applications. In a plain weave, yarns are interlaced in an alternating fashion and under every other yarn, providing maximum fabric stability and equal strength in any direction. The thinnest and lightest weight fabrics are also achieved through the plain weave.

Fig. 13 shows a representation of fractured specimens corresponding to different velocities at 21° C. All of them showed brittle failure. It can be observed that as the velocity was increased more damage resulted in the material. A cross-type of failure was prevalent at velocities of 2.31 m sec^{-1} (91 in sec^{-1}), 3.12 m sec^{-1} (123 in sec^{-1}) and 4.01 m sec^{-1} (158 in sec^{-1}). This type of cross failure is an indication of the equal strength in any direction. For a velocity of

TABLE II Curve fitting analysis for the maximum force dependence on temperature

Sample	F(N) = $a - bT$ (°C)	Regression coefficients
Two-sided copper laminate	$F = 2390 - 3.65\,T$	$R^2 = 0.91$
One-sided copper laminate, copper film facing dart	$F = 2213 - 3.86\,T$	$R^2 = 0.94$
One-sided copper laminate, copper film away from dart	$F = 2185 - 4.45\,T$	$R^2 = 0.80$

TABLE III Curve fitting analysis for the total energy dependence on temperature

Sample	E(J) = $a - bT$ (°C)	Regression coefficients
Two-sided copper laminates	$E = 14.04 - 0.0080\,T$	$R^2 = 0.73$
One-sided copper laminate, copper film facing dart	$E = 12.61 - 0.0082\,T$	$R^2 = 0.91$
One-sided copper laminate, copper film away from dart	$E = 12.68 - 0.015\,T$	$R^2 = 0.90$

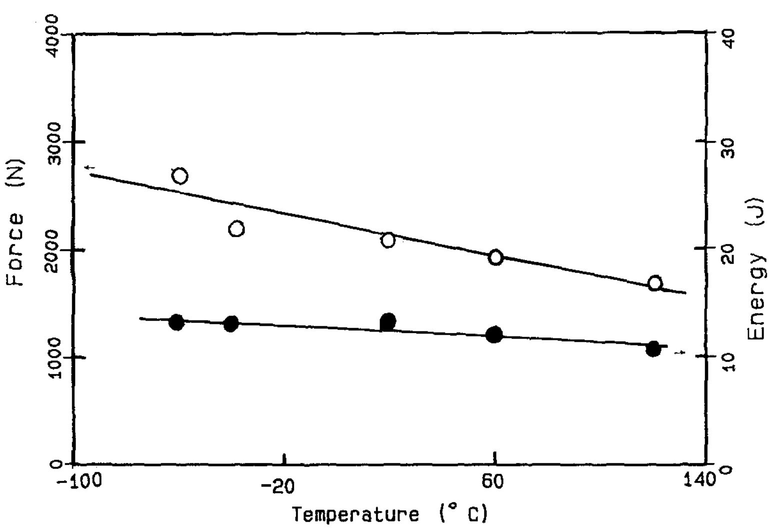


Figure 10 (○) Maximum force and (●) total energy dependence on temperature for the single-sided copper film laminate, copper film face down, at constant initial velocity of 123 in sec^{-1}.

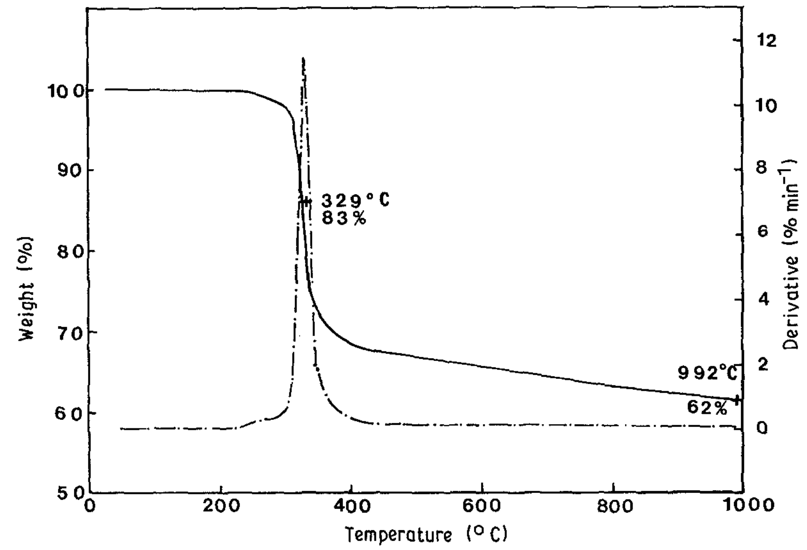


Figure 11 Percentage weight loss as a function of temperature for the double-sided copper laminate. (———) Weight, (—·—) derivative.

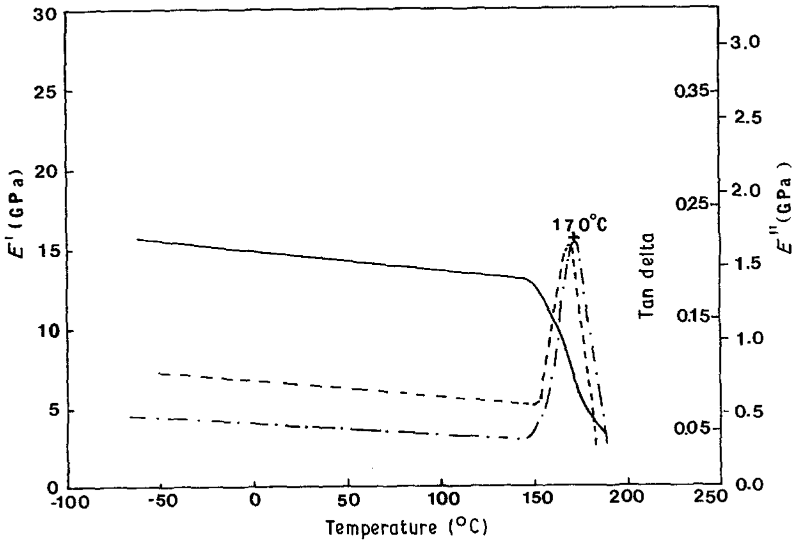


Figure 12 (———) Storage modulus, E', (– – –) loss modulus, E'', and (—·—) tan delta as a function of temperature for the one-sided copper laminate.

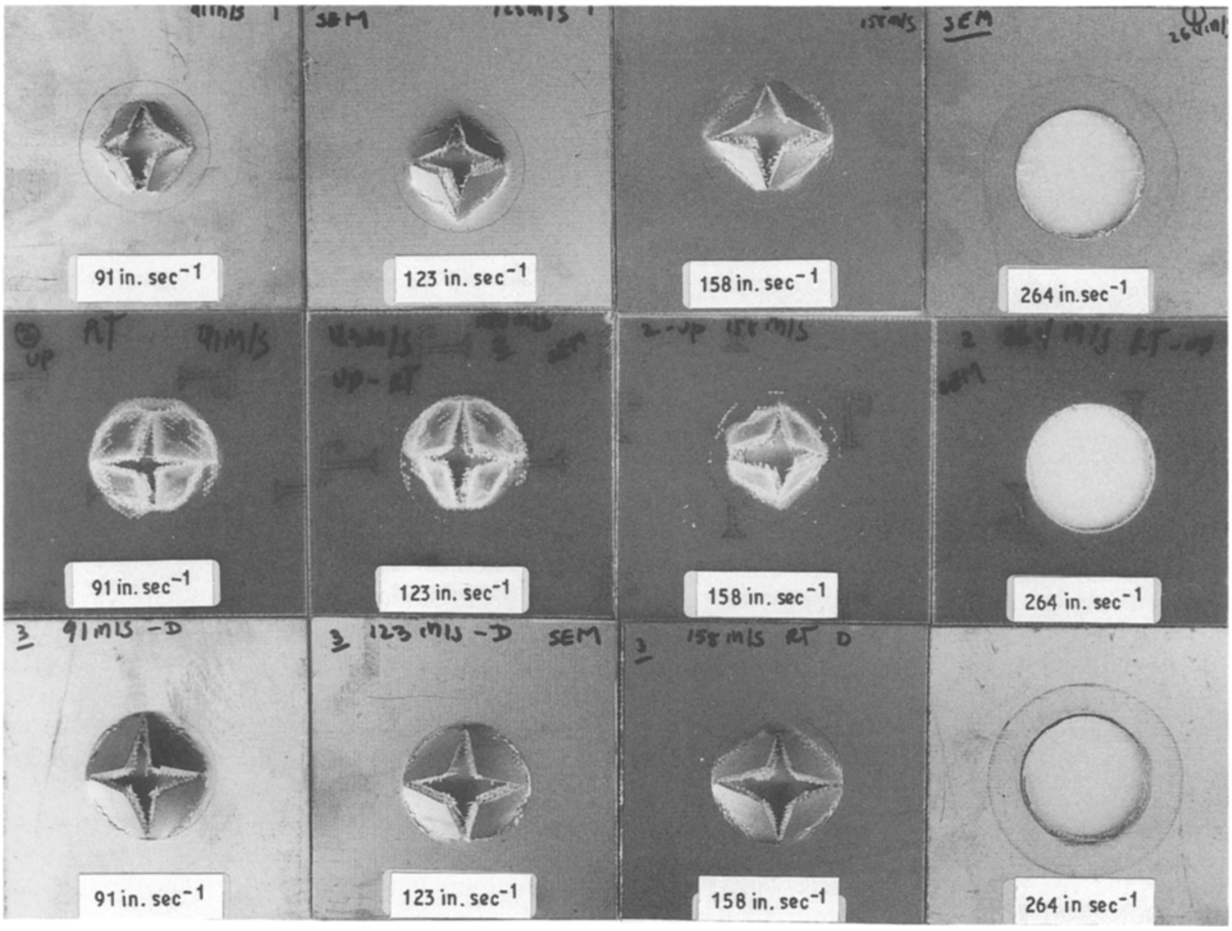


Figure 13 Fractured specimens as a function of the velocity of deformation.

6.70 m sec^{-1} (264 in sec^{-1}), a clean ring cut-off from the specimens was always observed.

Whitening areas (Fig. 14) were also present in the resin/glass composite. This indicated that delaminations and debonding between the glass and the matrix were also present in the damaged specimens. In addition, the copper film was always found to be well bonded to the epoxy resin/glass composite in the broken sample.

Scanning electron photomicrographs were taken for selected samples to determine the failure mode of the laminates. Fig. 15 shows photomicrographs of a one-sided copper layer specimen, the copper layer down at 4.01 m sec^{-1} (158 in sec^{-1}) and 21° C. A brittle failure with very little fibre pullout was observed. In these photomicrographs the glass bundles perpendicular to each other and the resin matrix between the glass bundles are well defined. Both the glass and the epoxy matrix showed brittle failure.

Fig. 16 shows representative photomicrographs of the surface failures of a specimen with the copper layer up at 4.01 m sec^{-1} (158 in sec^{-1}) and 21° C. The glass

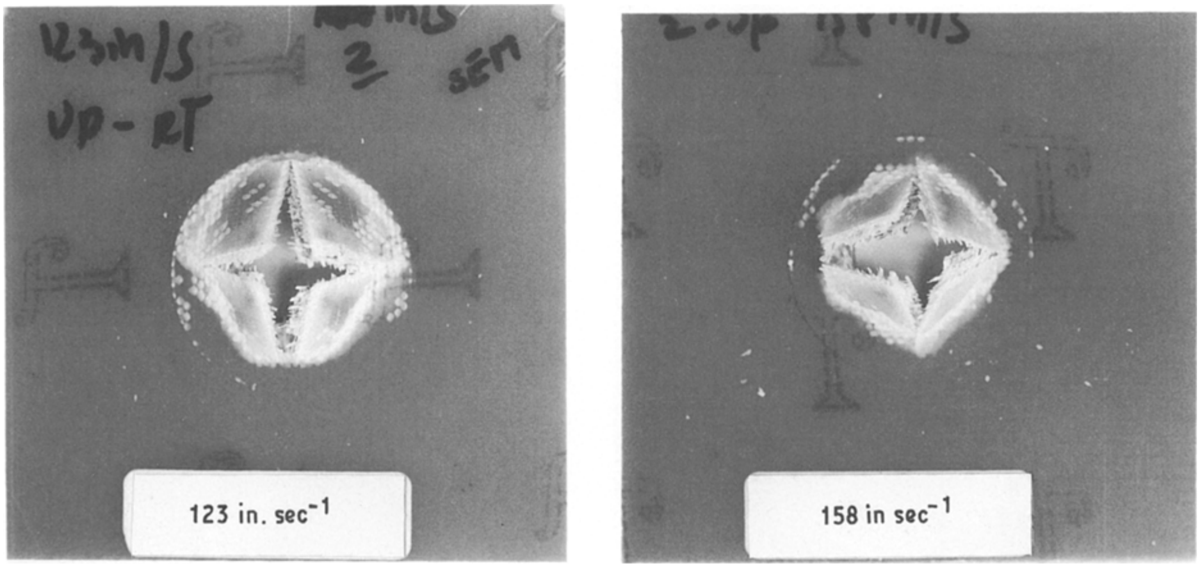
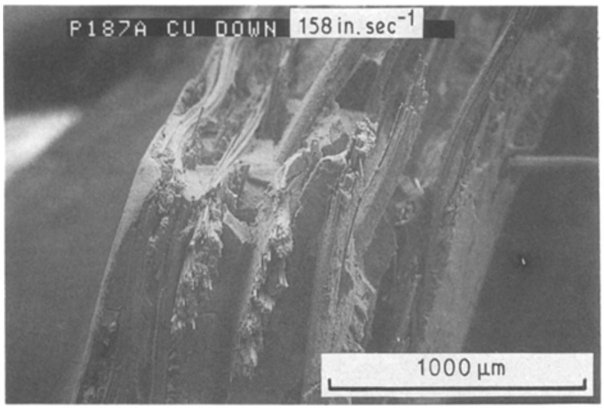
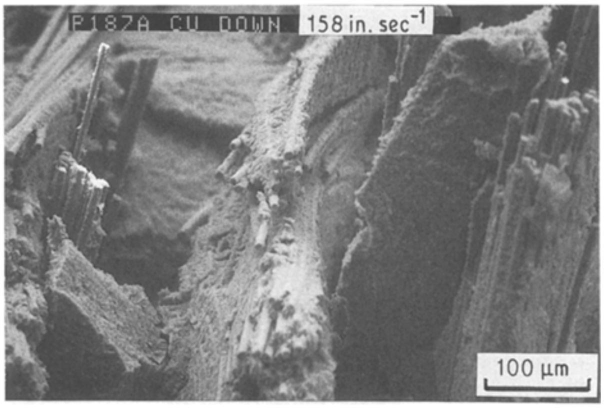


Figure 14 Illustration of the whitening areas in the resin/glass side.





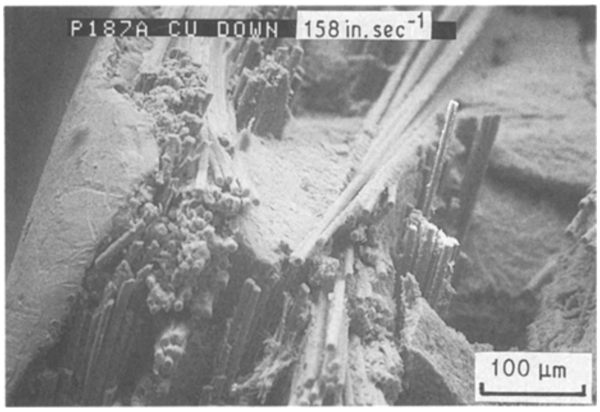


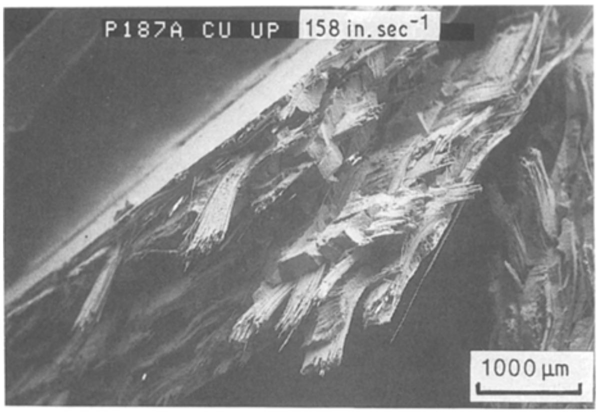
Figure 15 Scanning electron photomicrographs of the failure surfaces for a single-sided copper laminate, copper side down.

bundles and the resin showed brittle failures with some fibre pullout. Apparently, more fibre pullout was observed in this specimen (copper layer up) than for the previous sample (copper layer down, Fig. 15). This may be due to the higher impact load and energy values obtained for the specimen with the copper film up, facing the dart, where the copper film may have absorbed more impact energy. Therefore, the impact energy transmitted to the epoxy/glass component may have been less than for the case where the impacter first hit the glass fabric/epoxy side.

Fig. 17 shows scanning electron photomicrographs for the double-sided copper specimen at 4.01 m sec^{-1} (158 in sec^{-1}) and 21° C. Brittle failures in the resin and the glass, with some fibre pullout, were again observed.

In a dark instrumented impact test the stress state corresponds to biaxial bending. The cross-type of failure found in the laminates is related to the biaxial stress during impact. The deformation of the sample under dart nose in the first contact between dart and specimen is compression on the surface in contact with the probe and tension on the surface away from the dart nose. As the impacter goes through the specimen the tensile stress predominates and for a brittle material crack initiation takes place under tension. This crack will propagate due primarily to the tensile stress component, which will eventually result in the failure of the specimen. The surface failures observed under the scanning electron microscope were brittle failures due to tensile stresses.

The impact resistance of long and short fibre composites have been extensively evaluated [26]. For composite laminate, the nature of the matrix (either thermoplastic or thermoset), the type and length of the fibre (carbon, glass, or organic fibres), and the construction and thickness of the composite laminates



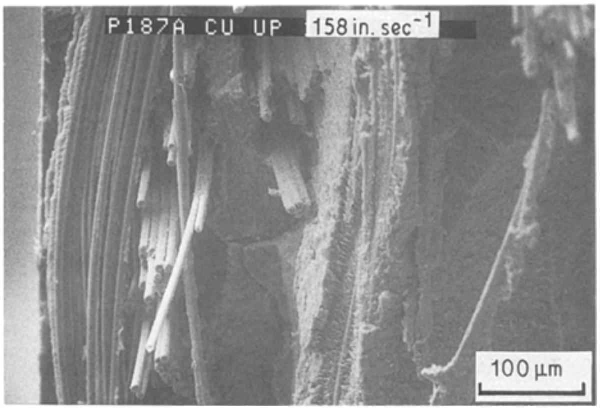
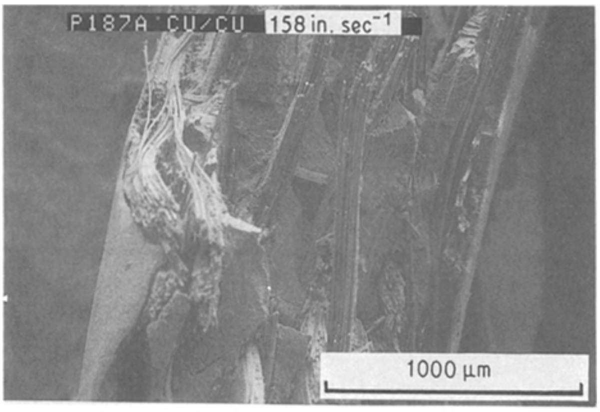
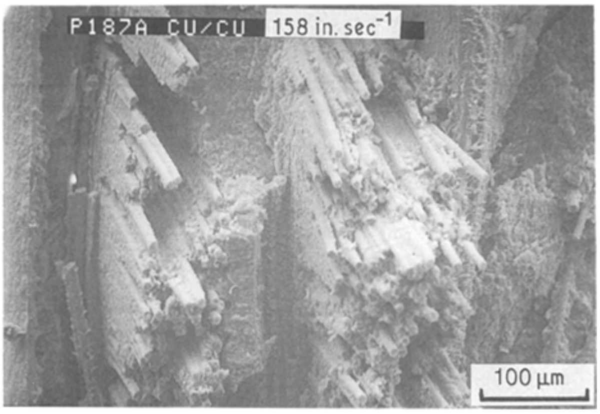


Figure 16 Scanning electron photomicrographs of the failure surfaces for a single-sided copper laminate, copper layer up.





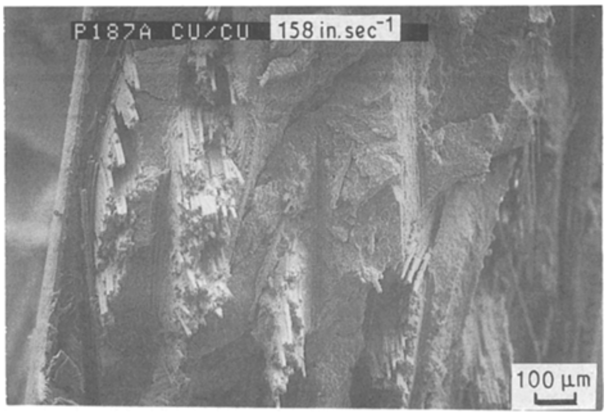


Figure 17 Scanning-electron photomicrographs of the failure surfaces for the double-sided copper laminate.

are, among others, important factors that will have an influence on their impact performance.

For composite laminates made out of carbon or glass fibres with an epoxy resin, having a nominal thickness of about 2 mm and an average of 60% fibre content (pre-preg materials), a brittle failure is commonly found using different impact techniques [26]. For example, Reed and Turner [16] reported a maximum force of 305 N and a total impact energy of 19.3 J for the composite Epoxy CF/S4 that contains approximately 69% of carbon fibres by weight. This type of relative highly loaded fibre laminate typically shows total impact energies below 100 J for thin laminates [15, 27]. Very little work has been reported on the puncture impact properties of copper-clad laminates for printed circuit board applications. As we have discussed, these materials are complex and other important issues, such as the effect of the thickness of the copper layer on the impact properties, as well as the quality of the bond adhesion between the copper film and the glass fabric/epoxy laminate, are topics for further research.

4. Conclusions

Copper film–epoxy–glass fabric laminates for printed circuit board applications were evaluated using an instrumented impact tester. For the single-sided copper film laminates, it was found that the orientation of the copper film with respect to the impact dart had an effect on the impact results. Higher fracture energy and fracture force were obtained for the case where the copper film was facing the dart. Double-sided copper film laminates gave the highest impact strength in the series. The maximum force was found to be independent of velocity and the total energy slightly increased with the initial velocity of deformation. Both the total energy and maximum force were found to decrease with the test temperature.

Double-sided copper film laminates performed better (with increased temperature) than single-sided copper laminates. This suggests that the copper film improves the dimension stability and temperature resistence of the laminates.

Fracture surfaces examined under the SEM indicated that failure of the specimen occurred as the result of biaxial stresses during impact. Brittle failure of the resin and glass fibres with some degree of fibre pullout was also present.

Acknowledgements

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