Dynamics of impact of sphere on flat surfaces of polymer matrix composites

MANISH ROY

Defence Metallurgical Research Laboratory, P.O. Kanchanbagh, Hyderabad 500 058, India

MS received 26 February 1999; revised 14 July 1999

Abstract. The primary objective of this work was to evaluate the influence of various reinforcements and matrix materials on the dynamic hardness of polymer matrix materials (PMC). Therefore, the impact of a WC ball, using a gravity drop system, was studied on PMCs. The two parameters, coefficient of restitution and dynamic hardness, of PMCs were determined. The mechanical properties of the PMCs were evaluated, and the correlation of the two parameters with the mechanical properties of PMCs was attempted.

Keywords. Polymer matrix composites; dynamics of impact.

1. Introduction

The dynamics of impact of a hard sphere on a flat surface primarily deals with the coefficient of restitution, and the modes of dissipation of kinetic energy of the sphere to the flat surface. Coefficient of restitution (e) is the ratio of the incident velocity to the rebound velocity, when a target material is impacted with an object. It is an important parameter that indicates the ability of the material to absorb energy. The coefficient of restitution, can be used for determining the dynamic hardness (H_d) which is the resistance of a material to indentation at very high strain rate (Tirupataiah *et al* 1990). This property is more relevant than static hardness for characterizing tribological behaviour of the material (Sundararajan 1995). The dynamics of impact of a sphere on a flat metallic surface have been studied extensively (Hertz and Reine 1891; Tabor 1948, 1951; Davis and Hunter 1960; Mock and Duffy 1965; Singer and Evans 1980). The elastic deformation during contact was treated by Hertz (1891), whereas subsequent plastic deformation was analysed by Tabor (1948, 1951), Mock and Duffy (1965) and others (Tabor 1951; Davis and Hunter 1960) who mainly considered the influence of impact velocity on the coefficient of restitution. However, the above-reported studies have not been carried out on polymer and polymer matrix composites. As the polymer matrix composites are considered to be potential material for tribological application, the present investigation has been undertaken to evaluate the influence of nature of matrix and nature of reinforcement on the value of e and in turn, on H_d dynamic hardness of the concerned material. The dependence of these two parameters on mechanical properties will also be examined.

2. Experimental

2.1 Material

Material used in this investigation can be broadly classified as PMC-I and PMC-II: PMC-I is a composite group of glass fibres, as the reinforcing material, and epoxy, polyester, modified phenolic, and unmodified phenolic resin, as the four different types of matrices; PMC-II is a composite group of epoxy resin, as the matrix, with unidirectional carbon fibre and three varieties of glass fibres viz. 4-weave plain satin, 8-weave plain satin, and plain weave, as the reinforcements. The matrix materials were prepared by dissolving commercially available resin powder in ethyl alcohol. The required size fibres were coated uniformly with the respective matrix resin. The resin-coated plies were then stacked inside a steel mould. While stacking, the orientation of the warp and weft fibre were maintained in all the plies. These plies were subsequently moulded in a hydraulic press at a pressure of 0.3 MPa at room temperature. For phenolic matrix composites, the resin-coated fibres were used to prepare the prepegs in an oven under set temperatures. These prepegs were subsequently stacked and pressed hydraulically (13.5 MPa, and 160°C).

2.2 Mechanical testing

The mechanical properties of the PMCs such as the tensile, flexural, and interlaminar shear strengths were determined using a screw-driven Tinius Olsen Universal Testing machine at a cross-head speed of 3 mm/min. Coefficient of restitution was determined in a gravity drop system as described below.

2.3 Determination of coefficient of restitution

The values of e of the test materials were determined using a gravity drop weight system. The schematic representation of the system is shown in figure 1. The impacting balls were stored in a ball feeder and allowed to drop freely on the target material under the influence of gravity. The test specimen, a flat sample, was fixed rigidly to the target holder at the bottom. The samples were always held normal to the path of the impacting ball.

The description of the system used for velocity measurement has been included with the method of

calculation for incident velocity, for rebound velocity, in the work by Tirupataiah *et al* (1990).

3. Results

3.1 Mechanical properties

Table 1 lists the various mechanical properties of the PMC-I, i.e. tensile strength, tensile modulus, flexural strength, flexural modulus, and interlaminar shear strength. These values are average of 3 tests with less than 10% deviation. From table 1, it is evident that glass phenolic resin (modified) exhibits highest tensile strength, flexural strength, interlaminar shear strength, and flexural modulus. In contrast, the highest tensile modulus is obtained for glass epoxy resin composite. Table 2 lists the various mechanical properties for PMC-II. A comparison between PMC-I and PMC-II indicates that the mechanical properties of the two groups are comparable. However among the PMC-II, epoxy matrix reinforced with unidirectional carbon fibre, has the best mechanical properties. In contrast, epoxy matrix reinforced with 4H satin weave glass fibre has the best interlaminar shear strength.

3.2 Coefficient of restitution

The values of (e) for PMC-I and PMC-II are presented in tables 3 and 4, respectively. Tables 3 and 4 indicate that e values of PMCs are substantially higher than those recorded for metallic materials by Tirupataiah *et al* (1990). Metals have values of e ranging from 0.1–0.4. Reinforcement of epoxy matrix by carbon fibre (unidirectional) increases e by 28% compared to PMC where epoxy resin matrix is reinforced by various glass fibres.

While the composite with epoxy resin as the matrix, in the PMC-I group, shows the highest e value (0.68), the composite with carbon fibres as the reinforcement, in the PMC-II, show the highest e value (0.82).

Figure 1. Schematic representation of the system.

Table 1. Mechanical properties of PMC-I.

Material	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Interlaminar shear strength (MPa)
Glass phenolic (unmodified) comp.	380	25.7	330	23.5	35
Glass phenolic (modified) comp.	475	42.6	470	42.5	49.5
Glass polyester comp.	340	40	267	30	26.5
Glass epoxy comp.	465	45	310	40	40

Table 2. Mechanical properties of PMC-II.

Material	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Interlaminar shear strength (MPa)
Epoxy reinforced with 8H satin weave glass fibres	450.8	31.8	620.1	27.5	38.5
Epoxy reinforced with 4H satin weave glass fibres	598.7	47.4	815.8	38.2	64.6
Epoxy reinforced with plain weave glass fibre	370.4	27.4	390.8	23.2	37.1
Epoxy reinforced with UD carbon fibre	723	67.7	1101.6	96.3	38.7

Table 3. Coefficient of restitution, dynamic hardness and strain rates during impact of PMC-I.

Material	Coefficient of restitution	Dynamic hardness (MPa)	Strain rate (sec ⁻¹)
Glass phenolic (unmodified) comp.	0.675	218.7	13.6
Glass phenolic (modified) comp.	0.625	286.4	14.6
Glass polyester comp.	0.635	280.3	14.5
Glass epoxy comp.	0.68	341.3	15.2

Table 4. Coefficient of restitution, dynamic hardness and strain rates during impact of PMC-II.

Material	Coefficient of restitution	Dynamic hardness (MPa)	Strain rate (sec ⁻¹)
Epoxy reinforced with 8H satin weave glass fibres	0.64	239.1	13.7
Epoxy reinforced with 4H satin weave glass fibres	0.64	321.9	15.0
Epoxy reinforced with plain weave glass fibres	0.66	224.5	13.7
Epoxy reinforced with UD carbon fibres	0.82	621.3	17.7

3.3 Dynamic hardness

As reported by Tirupataiah *et al* (1990), the coefficient of restitution (e) is related to the dynamic hardness, H_d , of the target material as:

$$e = \frac{1.9 H_d^{5/8}}{E_{\text{eff}}^{1/2} \rho_b^{1/8} V^{1/4}}, \quad (1)$$

and

$$H_d = 0.36 e^{8/5} E_{\text{eff}}^{4/5} \rho_b^{1/5} V^{2/5}, \quad (2)$$

where ρ_b is the density of the impacting ball, V the velocity of impact, and E_{eff} the effective modulus of the target-ball material combination, which on expansion can be written as:

$$E_{\text{eff}} = \frac{E_b E_f}{(1 - V_b^2) E_f + (1 - V_v^2) E_b}. \quad (3)$$

Thus, using expressions (2) and (3), dynamic hardness values of various PMCs have been determined. These values are given in tables 3 and 4. For PMC-I, glass-reinforced epoxy has the highest H_d ; and for PMC-II, unidirectional carbon fibre-reinforced epoxy has the highest H_d . The H_d of this composite is two times or more compared to the H_d of other composites.

4. Discussion

4.1 Strain rate

The average strain (ϵ_{av}) pertinent to the deformation conditions discussed above is given by Tabor (1951) as:

$$\epsilon_{\text{av}} = 0.1W/r, \quad (4)$$

where r is the ball radius, and W the crater diameter which upon expansion (Sundararajan 1991), can be written as:

Table 5. Correlation coefficient of the two parameters e , H_d with the mechanical properties of the PMCs.

Correlating parameters	PMC-I		PMC-II	
	e	H_d	e	H_d
e vs tensile strength				
H_d vs tensile strength	0.002	0.318	0.551	0.852
e vs tensile modulus				
H_d vs tensile modulus	0.117	0.864	0.711	0.935
e vs flexural strength				
H_d vs flexural strength	0.211	0.001	0.574	0.84
e vs flexural modulus				
H_d vs flexural	0.102	0.641	0.926	0.997
e vs interlaminar shear strength				
H_d vs interlaminar shear strength	0.025	0.068	0.127	0.006

$$W = 2.56 r \rho_b^{1/4} V^{1/2} / H_d^{1/4}. \quad (5)$$

The time of impact between the ball and various composites is given by (Tabor 1951; Hutching 1977) as:

$$t_{im} = 1.28 r \rho_b / H_d^{1/2}. \quad (6)$$

Thus average strain rate can be obtained as a ϵ_{av}/t_{im} or $\dot{\epsilon}_{av} = 0.2 V^{1/2} H_d^{1/4} / r \cdot \rho_b^{3/4}$. The strain rates obtained for various composites are given in tables 3 and 4. It is evident that the average strain rate is 12 to 17 sec^{-1} for the PMCs. This is the strain rate at which most of the metallic material undergoes abrasive wear, and this strain rate is lower than the strain rate to which metals and alloys are subjected during erosive wear (Sundararajan 1995).

However, a few points to which attention needs to be drawn are: (i) As the time of contact between the ball and the PMC is very small, and although deformation behaviour of polymers is known to be time dependent, in the present investigation, therefore time dependence of deformation behaviour can be ignored. (ii) The contact time being very small, therefore the heat generated by the impact cannot dissipate away, thus resulting in a fully adiabatic deformation. (iii) The state of stress during impact being multi-axial compressive, as in the case of hardness, therefore permits all the materials to deform plastically. Thus, considering all these points, the equations used above, though derived for metals and alloys, are applicable for PMCs also.

4.2 Correlation of e , H_d with the various mechanical properties

The coefficient of restitution and the dynamic hardness of these composites are correlated with their mechanical

properties. The correlation coefficient of the two parameters e , H_d with the mechanical properties, for PMC-I and PMC-II, are given in table 5. PMC-II shows better correlation of the two parameters with their mechanical properties than PMC-I. For all the composites, modulus correlate with e or H_d to higher extent than strength. Furthermore, the correlation between modulus and H_d is higher than the correlation between modulus and e . While, best correlation is obtained with flexural modulus for both e and H_d in PMC-II, tensile modulus exhibits better correlation with e and H_d in PMC-I. Thus, an improvement in stiffness would lead to an increase in its H_d and e . Interestingly, very poor correlation is noticed between interlaminar shear strength and e or H_d in all the PMCs. Interlaminar shear strength is dependent on the nature of fibre-matrix bond and does not affect e or H_d directly. Thus correlation coefficients do not indicate any simple method of estimating dynamic properties from mechanical tests such as modulus and strength.

5. Conclusions

- (I) Epoxy resin reinforced with unidirectional carbon fibre exhibits highest coefficient of restitution and dynamic hardness.
- (II) Stiffness is an important property to predict e and H_d of PMCs.
- (III) Interlaminar shear strength does not influence e and H_d of PMC.

Acknowledgements

The author is grateful to DRDO for funding this work. He is also grateful to Dr G Sundararajan, Director, International Advanced Research Centre for Powder Metallurgy and New Materials, Balapur, Hyderabad, for his constant encouragement.

References

- Davis C D and Hunter S C 1960 *J. Mech. Phys. Solids* **8** 235
- Hertz H and Reine 1891 *J. Angew. Math.* **92** 156
- Hutching I M 1977 *J. Phys. D. Appl. Phys.* **10** L179
- Mok C H and Duffy J 1965 *Int. J. Mech. Sci.* **7** 355
- Singer A R and Evans R W 1980 *Met. Technol.* **71** 142
- Sundararajan G 1991 *Wear* **145** 257
- Sundararajan G 1995 *Wear* **186,187** 129
- Tabor D 1948 *Proc. R. Soc. London Ser. A* **192** 247
- Tabor D 1951 *The hardness of metals* (Oxford: Clarendon Press)
- Tirupataiah Y, Venkataraman B and Sundararajan G 1990 *Mater. Sci. & Engg.* **A124** 133