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The wear resistance of glass fibre reinforced epoxy composites

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Polymers are usually characterized by low moduli and strength. Epoxy, as a thermoset material, has a low wear resistance. Additions of glass fibres improve the elastic modulus and tensile strength and can improve the wear resistance. The composites were prepared by pultrusion of the glass fibres after saturation of epoxy. The fibre volume fraction was varied up to 50%. Tensile and wear tests were carried out to examine the improvement in the composite properties. A small deviation of the tensile strength and the elastic modulus from the calculated values using the rule of mixture was observed due to the existence of porosities. The wear resistance increases with increasing the sliding velocity, with decreasing the applied contact pressure and with selecting the most favourable glass fibre volume fraction.

1. Introduction

Glass polymers of a great variety of types are now widely used, and many other types of fibres are being used to reinforce polymers. Polymers are usually characterized by low moduli and strength. This is due to the formability of the complex networks, and the sliding that can take place between the long chains. Compared to the ductile metals, they are not tough, and indeed some are very brittle, especially at temperatures below 0° C. Polymers are not resistant to heat [1].

Many strong filaments available for reinforcement purposes have strengths greater than 2400 MPa and with moduli larger than 3.5×10^5 MPa. The strong materials, which are light and also stiff, are ceramics-covalent solids such as B, C, B_4C, $B_{13}O_2$, B_6Si, AlB_3, SiC, BeO and Al_2O_3. These materials have high melting (or sublimation) points, high moduli and strength and low expansion coefficient. Fibres of glass with very smooth surfaces are very strong and relatively cheap. Epoxies are usually used for high performance load-bearing composites because of the the relative ease of producing the composite without damaging the fibres significantly, and without the need to chop the fibres into short lengths.

The attractive properties of glass fibre reinforced plastics include improved strength to density ratios, oxidation and corrosion resistance, high temperature strength, and electrical properties, increased thermal shock resistance, and the suitability for fabrication by variety of production methods [2]. Pultrusion is used as an easy method to fabricate very strong aligned fibre composites for high and low fibre volume fraction.

The aim of this investigation is to study the use of glass fibre reinforced epoxy composites, which have high modulus to weight ratio, in mechanical parts subject to wear and how this material can resist the wear?

2. Experimental technique

Continuous glass fibre of the type E-glass was used for reinforcement purposes and was supplied by Silenka, Holland. Epoxy resin was used as a binding material for the glass fibres. The resin (HY956) and the hardener (LY554) were supplied by Ciba Geigy and they were mixed with the ratio of 5:1 by weight, respectively. Pultrusion of the glass fibre and epoxy was achieved using a PVC tube of 12 mm inside diameter. The glass fibres were impregnated in epoxy resin after spreading to allow good saturation and distribution of the fibres. The fibres were pulled through the PVC tube to produce the desired cross-section of the product. The volume fraction of the fibres was varied as follows: 0, 10, 20, 30, 42 and 50 vol %.

Scanning electron microscope was used to examine the wear surfaces. The tensile test of the composites was carried out according to DIN 53455.

Wear tests under dry conditions were carried out on a pin-on-disc wear testing machine as described by Zamzam [3]. The wear pins (composites) have 10 mm diameter and 17 mm length. The contact pressure (p) and the sliding velocity (v) were varied as follows: p = 0.2, 0.4, 0.5, 0.6, 0.8, 1.0 MPa, and v = 0.347, 0.958, 1.906, 3.812, 9.524 m sec^{-1}. The wear discs were made of ball bearing steel (100 Cr 6) which have hardness of 64 HRC. The weight loss was measured every 5 km and the test ran up 55 km. The weight loss due to the wear of the pins was measured on an electric balance with an accuracy of ± 0.1 mg.

3. Results and discussion

3.1. Strength properties of the composites

The results in Figs 1 and 2 represent the effect of the glass volume fraction on both the composite ultimate tensile strength and the modulus of elasticity. In evaluating the strength of a reinforced plastic composite material the rule of mixture has been

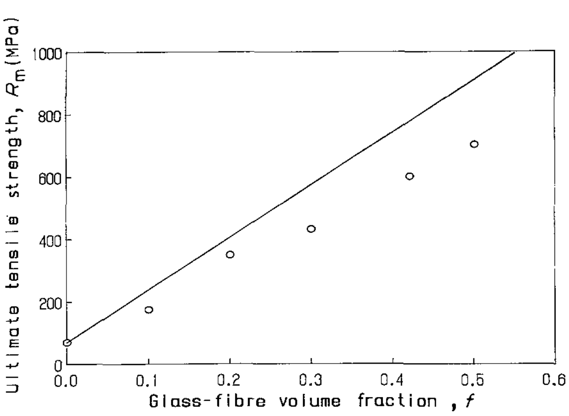

Figure 1 Effect of glass fibre volume fraction on the ultimate tensile strength of the composites. (— Theoretical results, ○ experimental results).

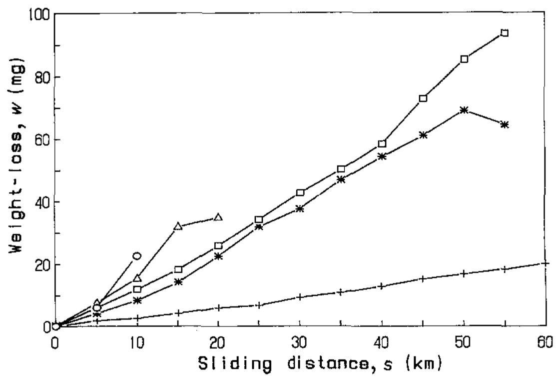

Figure 3 Weight-loss plotted against sliding distance for glass fibre reinforced epoxy composites. (○, $v = 0.347\,\text{m sec}^{-1}$, △, $v = 0.958\,\text{m sec}^{-1}$, □, $v = 1.906\,\text{m sec}^{-1}$, ∗, $v = 3.812\,\text{m sec}^{-1}$, +, $v = 9.524\,\text{m sec}^{-1}$). $p = 0.5\,\text{MPa}, f = 42\,\text{vol}\,\%$.

universally accepted as a preliminary step

$$R_{mc} = R_{mf} f + R'_{mm}(1 - f) \quad (1)$$

$$E_c = E_f f + E_m(1 - f) \quad (2)$$

where R_{mc} is the composite strength, R_{mf} the fibre strength, R'_{mm} the matrix strength corresponding to the fibre fracture strain, E_c the composite modulus of elasticity, E_f the fibre modulus of elasticity, E_m the matrix modulus of elasticity and f the fibre volume fraction.

Although it is well known from advanced studies [2, 4, 5] of the composite strengths that the above relations signify only a guidance to the composite strength, it is often observed that the strengths in practice show lower values than those obtained through theoretical estimation by applying the rule of mixtures. These observed lower values can be broadly attributed to

(a) insufficient bonding,
(b) internal porosity,
(c) inherent material defects.

Many investigators [2, 4, 5] found that the composite strength decreased very rapidly at low fractional porosities of the fibres and the effect is predominant at large volume fraction of the fibres in the matrix. It was noticed that the porosity volume increases with increasing the fibre volume fraction (porosity = 1.8, 3.6, 4.5, 4.2 and 5.8 % for f = 10, 20, 30, 42 and 50 vol %, respectively). The porosities exist in the epoxy–matrix and at the fibre–matrix interface. No significant features were observed to show insufficient bonding or inherent material defects in the composites.

3.2. Wear behaviour of the composites
3.2.1. Effect of sliding velocity on the composite wear resistance

The data in Fig. 3 show that for any given specimen the weight loss continuously increases with increasing the sliding distance for any different sliding velocities. The results in Figs 3 and 4 display the wear of 42 vol % glass fibre reinforced epoxy under an applied normal contact pressure of 0.5 MPa for different sliding velocities ranging from 0.347 to $9.624\,\text{m sec}^{-1}$. The trends established are first, the wear resistance of the composites increases slowly with increasing the sliding velocity up to $3.912\,\text{m sec}^{-1}$ followed by abrupt increase in the wear resistance and, second, decreasing the sliding velocity leads to a severe wear of the composites especially for velocities smaller than $1.906\,\text{m sec}^{-1}$. This may be due to the high adhesion between the composite and the steel counterface especially at low sliding velocity which is responsible for the increase in the wear rate and as the velocity increased, the tendency to adhesion decreased. This decrease in the adhesion can be attributed to the generated heat during the wear test at high velocity which is responsible for oxidizing the abraded iron particles resulting from the steel counterface which

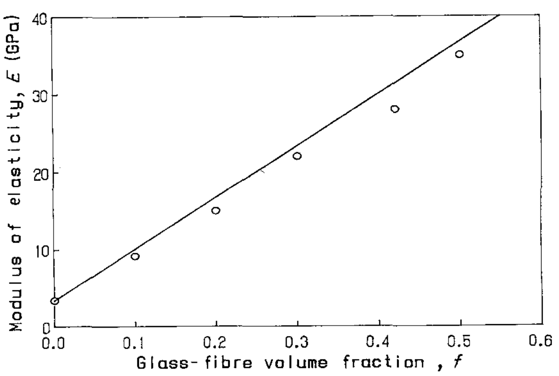

Figure 2 Effect of glass fibre volume fraction on the composite modulus of elasticity. (— Theoretical results, ○ experimental results).

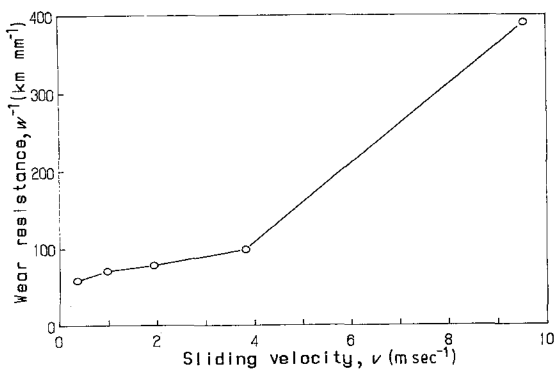

Figure 4 Wear resistance plotted against sliding velocity for glass fibre reinforced epoxy composites. (○ $p = 0.5\,\text{MPa}$) $f = 42\,\text{vol}\,\%$.

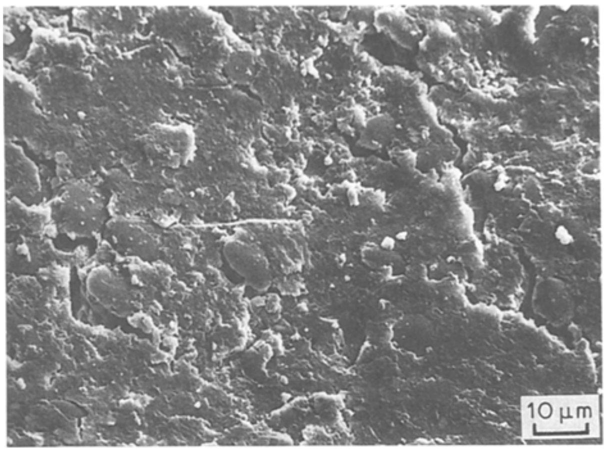

Figure 5 The compacted iron oxide (τ-Fe_2O_3) over the composite pin.

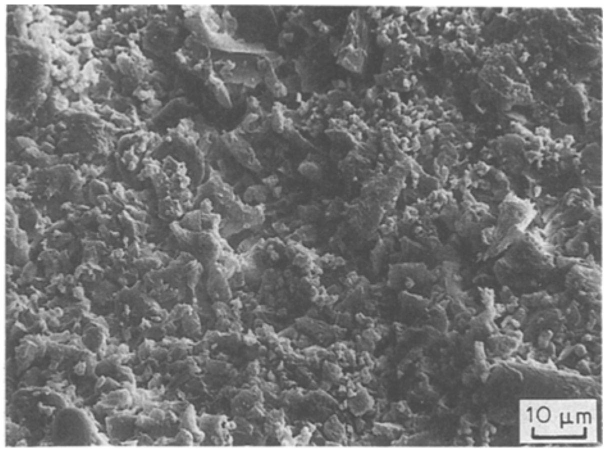

Figure 7 The loose iron oxide (α-Fe_2O_3) over the composite pin.

in turn adhere to the surface of the composite pin and therefore decrease the wear rate, Fig. 5. With decreasing the sliding velocity, the subsurface undergoes repeated loading at increasing stress levels as the stress levels of the welded joints increase, Fig. 6. This causes a fatigue type of failure in the substrate, resulting in wear which increases with decreasing velocity. The present results are in good agreement with the results of Tanaka and Yamada [6] who investigated the wear behaviour of unreinforced thermoplastics. The results of Voss and Friedrich [7] for glass fibre reinforced thermoplastics showed that no perceptible trend was established between the sliding velocity and the wear rate for the lower contact pressure. At higher contact pressure, they found that by increasing the sliding velocity the wear rate increases which is in contradiction to the present results. Moreover, the generated heat may have a great effect on increasing the tendency to adhesion between the sliding parts. The appearance of the contact surface of specimens tested at sliding velocity of 9.624 m sec^{-1} is red–brown in colour (which is α-Fe_2O_3), as shown in Fig. 7, while specimens tested at 1.906 and 3.812 m sec^{-1} have a black colour (τ-Fe_2O_3), as seen in Fig. 5. The specimens that are tested at 0.347 and 0.958 m sec^{-1} appear just the same as the fresh surface of the composites.

The wear resistance of these composites ranges from 80 to 400 km mm^{-1} which is greater than the wear resistance of PTFE against hardened steel [8], glass fibre reinforced polyamide-6.6 [7], carbon fibre reinforced acetal [9] and alumina fibre reinforced aluminium composites [10].

3.2.2. Effect of contact pressure on the composite wear resistance

Figs 11 and 12 show the wear data obtained under different applied normal contact pressures up to 1.0 MPa. It is clear that the weight loss increases with increasing the sliding distance and the contact pressure. A rapid failure of the composite pins was noticed for specimens tested at 0.2 and 0.4 MPa contact pressure just after 20 km sliding distance so the wear tracks on the discs became smeared with a layer of epoxy within a short period. Subsequent wear took place between this transferred layer and the test specimen, thus promoting seizure. The appearance of the failed specimens is shown in Figs 8, 9 and 10c. The other specimens withstood wear up to 1.0 MPa contact pressure without failure. This can be attributed to the generated heat during the test which was responsible for the transformation of iron to one modification of its oxide that adhered to the contact surface of the pins and prevented failure (severe wear). Increasing the contact pressure led to a linear decrease in the wear resistance of the composites, Fig. 12. This result is in

Figure 6 Failure cracks at the fibre–matrix interface and between the fibres.

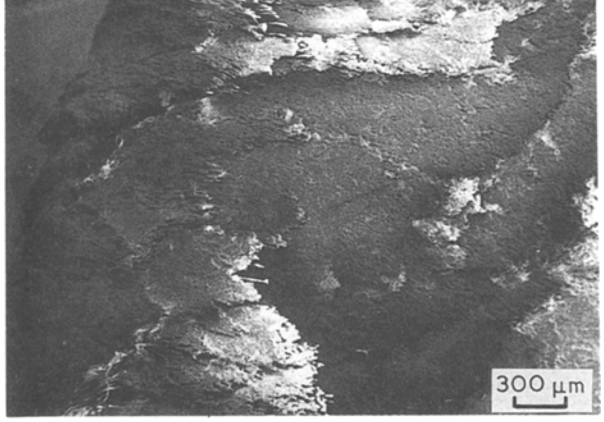

Figure 8 Severe wear of the composite pin showing the fibrous structure.

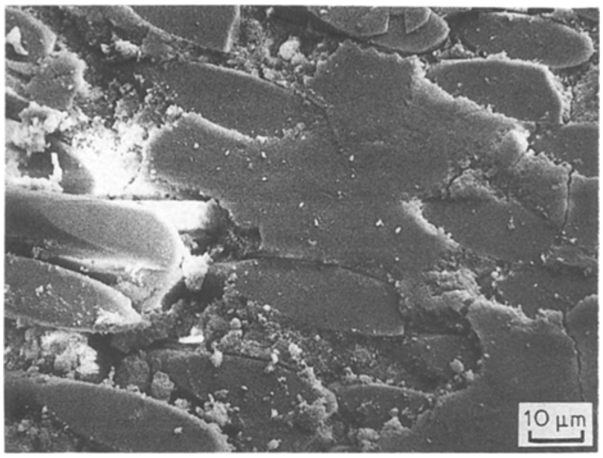

Figure 9 Severe wear of the composite pin showing the wear of the fibres.

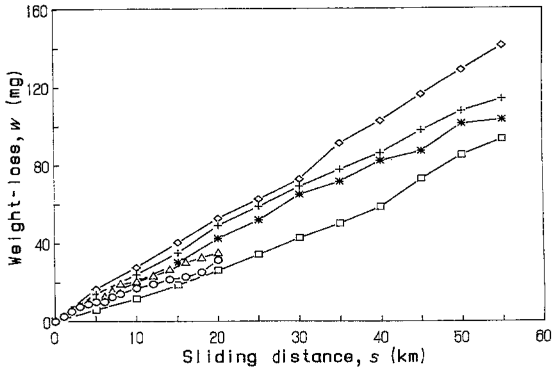

Figure 11 Weight-loss plotted against sliding distance for glass fibre reinforced epoxy composites. (○, $p = 0.2$ MPa, △, $p = 0.4$.MPa, □, $p = 0.5$ MPa, *, $p = 0.6$ MPa, +, $p = 0.8$ MPa, ◇, $p = 1.0$ MPa) $v = 1.906\,\text{m sec}^{-1}$, $f = 42$ vol %.

a good agreement with the results obtained by Zum-Gahr [11] for many sliding partners. Reinforced fibres influence wear by supporting the applied load with less deformation than the pure matrix, due to their greater strength and elastic modulus, hence, they carry a proportionally greater part of the load than their volume fraction. Voss and Friedrich [7] come to the conclusion that the influence of the sliding speed on the wear rate seems to be the more detrimental variable than the contact pressure which is in good agreement with the present results. The colour of the wear surfaces of the tested pins up to 0.4 MPa contact pressure was just the same as the fresh composite, which the tested specimens beyond this contact pressure are black in colour.

3.2.3. Effect of glass fibre volume fraction

The effect of glass fibre volume fraction on the wear behaviour of the composites is shown in Figs 13 and 14. The results in Fig. 13 show that for all fibre fractions the weight-loss increases with increasing the sliding distance. A catastrophic wear of epoxy was noticed so the specimens wore down quickly at 3 km sliding distance, as in Fig. 10c. Increasing the fibre volume fraction led to improve the composite wear behaviour and retarded the occurrence of severe wear so the specimens wore down at higher sliding distances, e.g. composites having fibres of 10, 20 and 50 vol % wore down at sliding distances of 12, 24 and 44 km, respectively, while the specimens with 30 and 42 vol % fibres withstood mild wear up to 55 km.

The effect of the volume fraction on the wear resistance is shown in Fig. 14. Here is an interesting result that the wear resistance remarkably increases with the volume fraction of the fibre up to 30% after which it decreases again. The decrease in the wear resistance can be attributed to insufficient bonding between the fibres due to the decrease in the resin (matrix) with increasing the fibre fraction, as seen in Fig. 6. The amount of epoxy in specimens containing 50 vol % fibres seems to be insufficient to withstand the frictional forces appearing during the wear test. Therefore, cracks will initiate and propagate in the epoxy matrix leading to failure of the bonding between the fibres. As a result, the contact surface of the worn specimens appears as brush as shown in Fig. 10c. It can be concluded that at low fibre fraction, the wear behaviour of the composite is dominated by the friction and wear properties of the matrix, whereas at higher fibre volume fraction, wear mechanisms associated with the fibres effectively determine the composite wear rates. Finally this can even lead to an increase in wear rate with further increase of fibre reinforcement which is obviously seen in the results in Fig. 14. Similar results were found by Friedrich [7, 12] for glass fibre reinforced thermoplastics. In order to describe such behaviour, the wear mechanisms occurring in the contact area should be known and how they contribute to

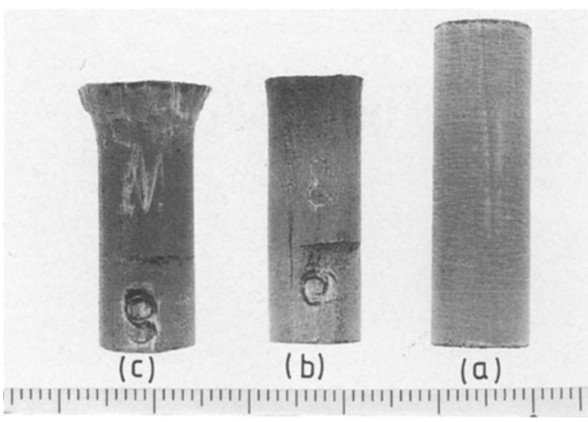

Figure 10 Shape of the wear specimens (a) before the test (b), after mild wear and (c) after severe wear.

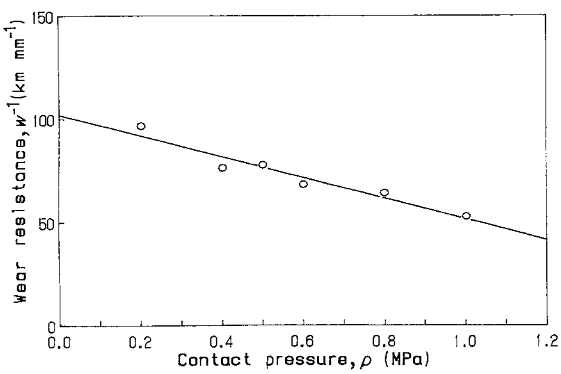

Figure 12 Wear resistance plotted against contact pressure for glass fibre reinforced epoxy composites. (○, $v = 1.906\,\text{m sec}^{-1}$) $f = 42$ vol %.

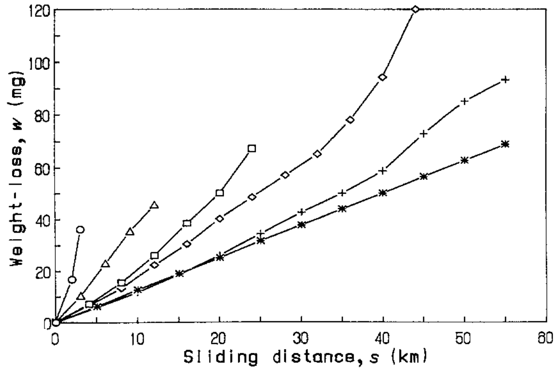

Figure 13 Weight-loss plotted against sliding distance for glass fibre reinforced epoxy composites. (○, f = 0 vol %, △, f = 10 vol %, □, f = 20 vol %, *, f = 30 vol %, +, f = 42 vol %, ◇, f = 50 vol %) v = 1.906 m sec^{-1}, p = 0.5 MPa.

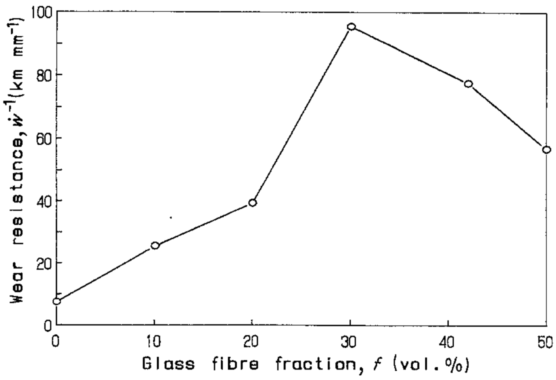

Figure 14 Wear resistance plotted against glass fibre volume fraction for glass fibre reinforced epoxy composites. (○, v = 1.906 m sec^{-1}). p = 0.5 MPa.

the wear resistance of the composites. There are five individual mechanisms which dominate the process of material removal:

(1) Matrix wear,

(2) Fibre sliding wear,

(3) Debonding of the fibres from the matrix, Fig. 6,

(4) Plastic deformation of the matrix up to fracture,

(5) Severe sliding wear of the composite, Figs 8 and 9.

It is clear that mechanisms 3, 4 and 5 occur sequentially and, therefore, they can be considered as a combined process of fibre cracking and interfacial separation, hence, the interfacial bond between matrix and fibres plays an important role in the wear process.

4. Conclusions

From the previous discussion, the following conclusions can be stated.

(1) The existence of the matrix porosities is responsible for the deviation of the composite tensile strength and modulus of elasticity from the theoretical values calculated using the rule of mixture especially at high volume fraction of fibres.

(2) A pronounced increase in the wear resistance of the composites was found with increasing the sliding velocity.

(3) Increasing the fibre volume fraction retarded the occurrence of severe wear up to a certain fraction at which debonding of the fibres from the matrix, plastic deformation of the matrix up to fracture and severe wear took place.

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