A NOVEL MANUFACTURING METHOD FOR ALIGNED SHORT FIBRE COMPOSITE

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Abstract
Highly aligned discontinuous fibre reinforced composites can achieve high performances provided the aspect ratio is sufficiently high to guarantee a high load transfer capability. Discontinuous fibres offer the scope to create a ductile response by deformation and slip at the discontinuities. The aim of this research is to develop a manufacturing process for preforms with highly aligned reinforcement directly from short fibres rather than from a pre-existing tow for high performance ductile properties of composites. This paper introduces the conventional flow-induced short fibre alignment methods and analyzes their manufacturing process based on Axiomatic Design theory and also provides a novel short fibre alignment method. Feasibility tests of this new method using water as a fibre suspension medium have been performed and resulted in getting a highly aligned tow type preform.

1 Introduction

Composites achieve their high specific strength and stiffness by aligning the fibres, which also allows a high volume fraction to be attained. High performance materials have mainly used continuous fibres, but these can fail in a catastrophic way due to their brittleness. Highly aligned discontinuous fibre reinforced composites can also achieve high performance provided the aspect ratio is sufficiently high to guarantee a high load transfer capability. Furthermore, complex structural shapes which cannot readily be fabricated using continuous fibres could be produced while retaining the high performance. The discontinuous fibres provide ductility during molding, but also offer the scope to create a ductile or pseudo-ductile response under loading by deformation and slip at the discontinuities.

The aim of this research is therefore to manufacture highly aligned discontinuous preforms directly from short fibres rather than from a pre-existing tow. The manufacturing method should allow hybridization with different fibre types in the fibre length range of 0.1~5 mm, and offer closed loop recycling of the fibres as well as the complete system with an appropriate choice of matrix.

Several techniques using pneumatic, electrical, magnetic or hydraulic means have been tried in the past to orient fibres in a preferred direction while processing discontinuous fibre composites [1]. Pneumatic methods have been used as a dry fibre handling process from earlier work, such as combing, teasing and carding in the textile industry. Later achievements include aligning glass-mat reinforced thermoplastics (GMT) by firing bindered glass strands

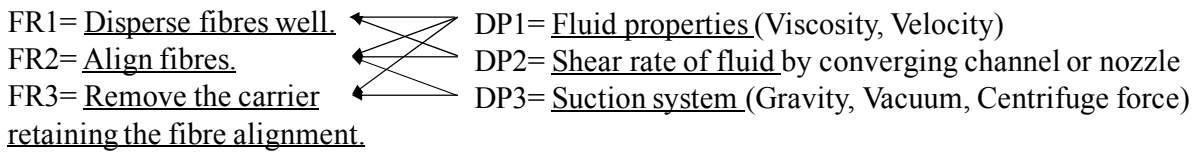
onto orientated plates at the end of fibre delivery tubes [2,3]. However, these methods are limited to a particular length of fibre. Electrical and magnetic field induced alignment methods also have advantages with controlling the dry short fibres but need high intensity so they could cause health and safety problems and they have a limitation of fibre types. In general, pneumatic and electric or magnetic field methods cannot allow the creation of aligned preforms with high orientation levels. The alignment from electric field methods is typically only 70% of fibres in the range of ±20° [4].
Wet processing methods have achieved some success with high alignment level with all fibres in the range of ±4°. Fibre alignment is achieved by accelerating the carrier medium through a converging nozzle, forcing the fibres to follow the fluid streamlines [2]. This method can allow hybridization of fibres. There is no limitation of fibre types and it is suitable for 0.1~5 mm long fibres. Therefore, the flow-induced alignment method could be suitable for the research aim, but significant reductions in fabrication times or costs need to be achieved.
This paper introduces the conventional flow-induced short fibre alignment methods and considers their limitations by analyzing the manufacturing process based on Axiomatic Design for developing a novel short fibre alignment method. A design concept for a new method using water as a fibre suspension medium has been generated. A feasibility test for 3 mm long carbon fibre was performed and the fibre orientation level of the preform was also investigated.

2 Limitations of conventional flow-induced short fibre alignment methods based on Axiomatic Design

Axiomatic Design is one of the system design methodologies using matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables [5]. Specifically, functional requirements (FRs) are related to design parameters (DPs). Discontinuous fibre alignment process can be resolved into three separate unit operations. These can be defined as three functional requirements of the alignment method using Axiomatic Design theory as follows [6],

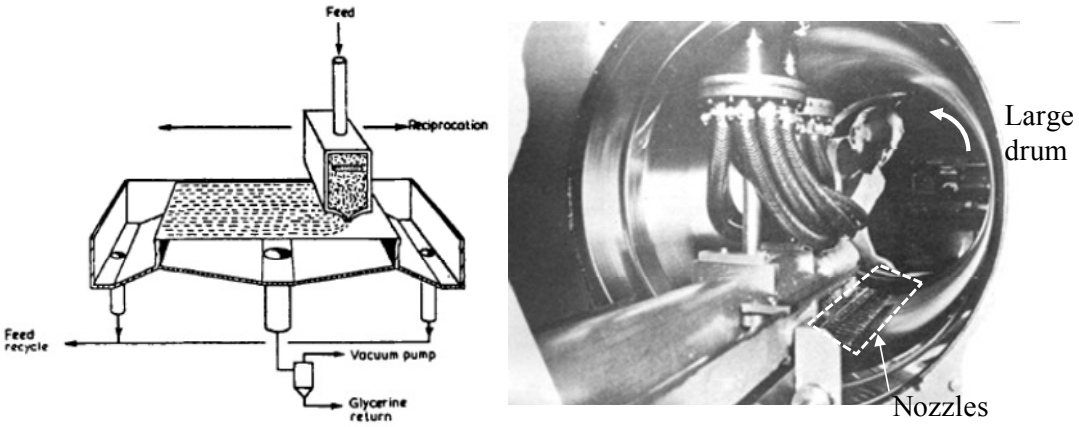
FR1= Disperse fibres well. (The dispersion must be sufficiently stable during the ensuring processes to prevent flocculation.)
FR2= Align fibres. (Any forces to align fibres must be applied.)
FR3= Remove the carrier retaining the fibre alignment. (The removal of the carrier must be rapid and complete, and must not disturb the fibres.)

There are several examples of the wet processing method using glycerine such as the PERME (Propellants, Explosives and Rocket Motor Establishment, Ministry of Defence, UK [6,7]) filtration process, centrifuge alignment process, and MBB-VTF (MBB: Messerschmitt-Bölkow-Blohm GmbH, Germany, VTF: Vacuum-Drum-Filter [8]) process. In this method, it is found that FR1-3 and DP1-3 could be defined as shown below.



Constraints of this process design are the manufacturing time and cost and the continuous process for fibres with length from 0.1 to 5 mm.
The PERME filtration process using a high-viscous liquid achieves fibre alignment by submitting a suspension of fibres to a shear flow field. A fibre mat is formed by extruding the

suspension through a slit in a V-shaped trough which is reciprocated over a filter bed as shown in Figure 1(a) [6]. The suspending fluid should be then removed by strong suction. But removing the carrier rapidly can be difficult and can cause fibre misalignment due to the high viscosity of the fluid. The centrifuge alignment process has been developed to overcome some of the problems associated with the filtration process described above. Alignment in this process is achieved by ejecting a suspension of fibres through a tapered nozzle, see Figure 1(b) [7,9]. The mat is formed by reciprocating the jet over a permeable cylinder. The cylinder rotates with an angular velocity that is sufficient to force the suspension through the surface and a layer of aligned fibres is thereby deposited on the surface of the cylinder. The MBB-VTF method is a similar process which uses a rotating vacuum drum filter to align fibres in suspensions [8,10].



(a) (b)

Figure 1. (a) Schematic diagram of the filtration plant [6], (b) large centrifuge alignment plant [7].

The above methods employed a converging channel or nozzle to make the shear flow field in order to align the fibres and the vacuum or centrifuge force to remove the carrier from the fibre suspension rapidly. FR1 and 2 can be satisfied if the carrier is a viscous liquid, especially, FR2 requires a high-viscous liquid to create a large shear rate in the fluid. However, FR3 needs the viscosity to be low for rapid manufacturing. The fluid characteristic of DP1 affects all functional requirements of the process design and the value of DP1 that each FR wants is different. In Axiomatic Design theory, we call that a coupled design [11] and the design matrix could be written as shown in equation (1).

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ X & 0 & X \end{pmatrix} \begin{pmatrix} DP1 \\ DP2 \\ DP3 \end{pmatrix} = \begin{pmatrix} FR1 \\ FR2 \\ FR3 \end{pmatrix} \tag{1}$$

Long production times are therefore inevitable and this consequently limits the output of glycerine processes to around 4 kg/h [2].

The paper making industry has achieved some success but alignment is insufficient to obtain high performance composites [6] because it is also a coupled design. The paper making process differs from the glycerine process in that it uses a low-viscous medium to satisfy FR3 rather than FR2.

Consequently, conventional methods cannot achieve high alignment levels of the reinforcements and reduction of manufacturing time and cost at the same time.

3 New discontinuous fibre alignment method

3.1 Concept generation with Axiomatic Design

This paper suggests a new discontinuous fibre alignment method with Axiomatic Design to set up proper design parameters. First of all, water is chosen as the carrier because it has enough viscosity to disperse fibres with length from 0.1 to 5 mm while satisfying the constraints of manufacturing time. Second, the water (fibre suspension) jet from the nozzle on the end of a water pump flows through the orientation head consisting of two inclined plates. Subsequently, the fibres in the suspension hit the inclined plate and then the orientation of them can be changed perpendicular to the water jet direction if *d* the distance between the two inclined plates is less than the fibre length. Finally, the water is removed rapidly and easily by the perforated weave with vacuum. A schematic of this process is shown in Figure 2.

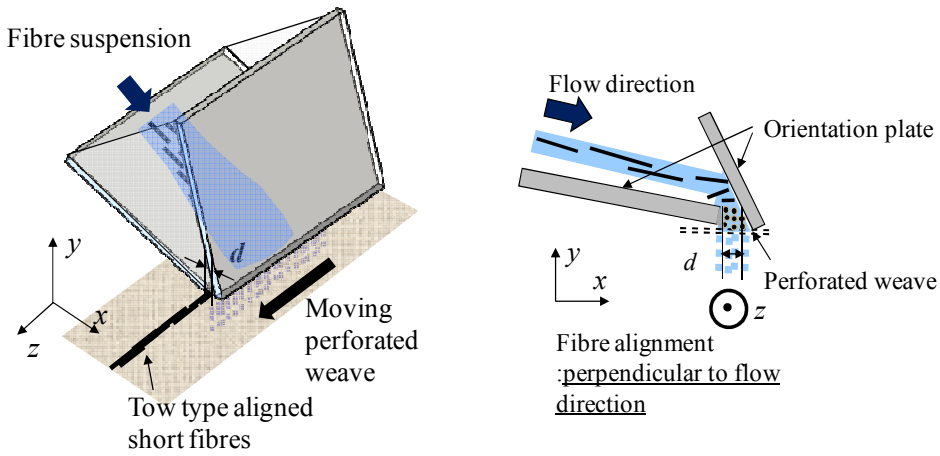


Figure 2. Schematic of new discontinuous fibre alignment method.

We can therefore summarize the definition of design parameters in this process as follows,

FR1= Disperse fibres well. ← DP1= Fluid properties (Viscosity, Velocity)
FR2= Align fibres. ← DP2= Mechanical force by hitting the orientation plate
FR3= Remove the carrier retaining the fibre alignment. ← DP3= Suction system (Vacuum)

The design matrix of this process could be represented as a lower triangular matrix as shown below and it is a decoupled design in Axiomatic Design theory [5,11].

$$\begin{pmatrix} X & 0 & 0 \\ x & X & 0 \\ x & 0 & X \end{pmatrix} \begin{pmatrix} DP1 \\ DP2 \\ DP3 \end{pmatrix} = \begin{pmatrix} FR1 \\ FR2 \\ FR3 \end{pmatrix} \tag{2}$$

FR2 and FR3 can be controlled by DP2 and DP3 regardless of the liquid suspension properties although DP1 would have little effect on FR2 and 3. Therefore, from this design concept, we could expect a fast and continuous process with highly aligned tow type preforms.

3.2 Feasibility test

3.2.1 Materials and experimental setup

To verify the design concept experimentally, a fibre suspension and a small device were prepared. The carbon fibres are 1.8 g/cm^3, 3 mm, and 7 μm in density, length and diameter,

respectively. The fibres sized with a water-soluble polymer of 3.8% (volume fraction) were supplied from Toho Tenax GmbH. The suspending fluid is tap water whose density is 0.99 g/cm^3 at a temperature of 25°C. The dynamic viscosity of the water is 0.001 kg/ms. The carbon fibres were put into the water at a weight fraction of 0.025%. This fibre suspension was treated by an ultrasonicator for 15 minutes for good dispersion and it is in the semi-dilute regime based on the crowding number *N* which was found by Kerekes&Schell to be useful to characterize the regimes of fibre concentration and flocculation in water [12]. The water (fibre suspension) jet was supplied to the orientation head by a syringe. The device includes the orientation head and the suction system. The orientation head consists of two inclined plates with angles that are adjustable and the suction system consists of the vacuum ejector, moving perforated weave, and suction plate with a slit applying a vacuum to remove the water as shown in Figure 3(a) and (b) .

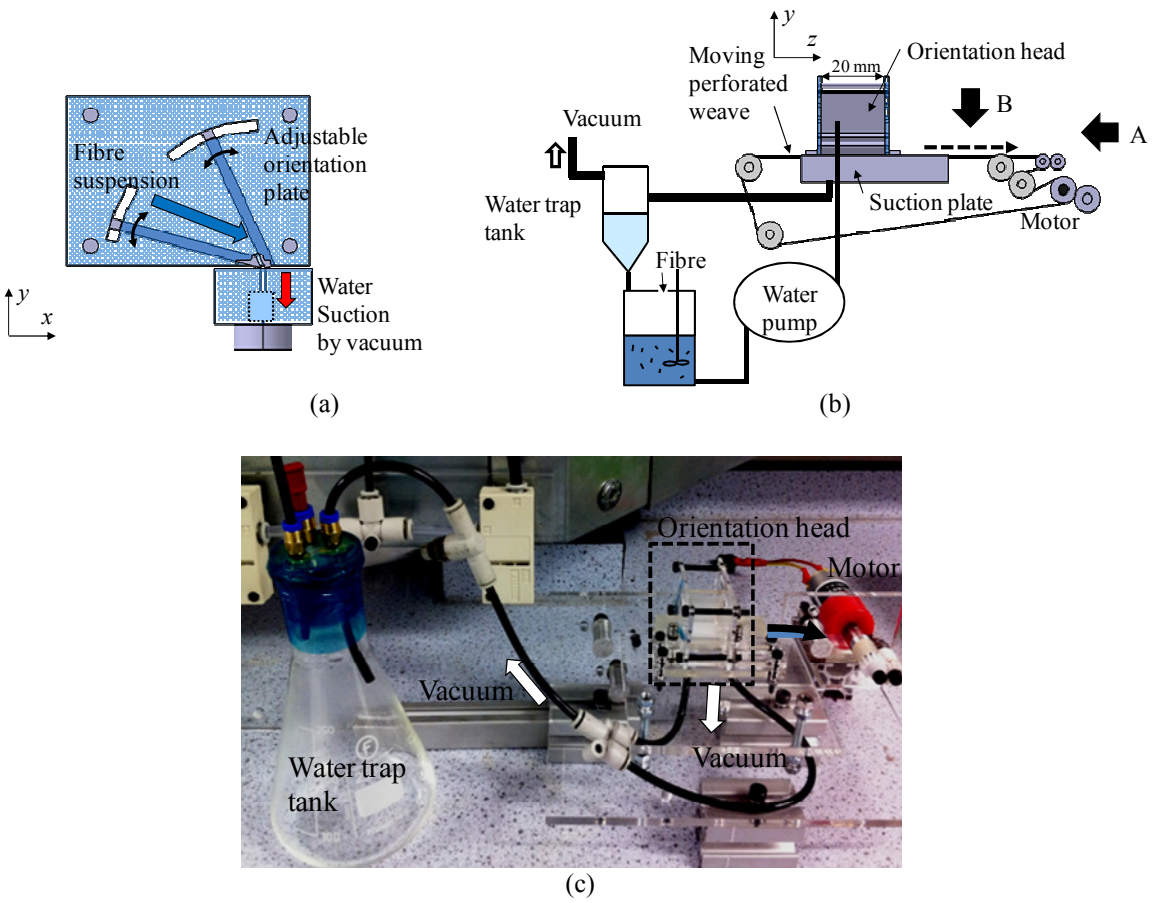
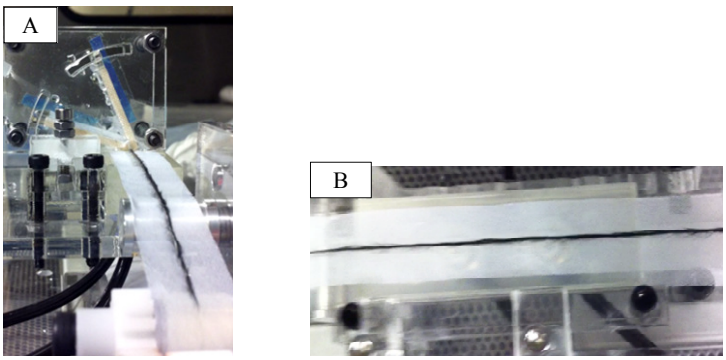


Figure 3. (a) Orientation head and suction plate design in x-y plane and (b) Schematic diagram, (c) actual devices for feasibility test.

A water trap tank is placed between them to avoid damage to the vacuum ejector. The level of vacuum was -75 kPa. The moving perforated weave is placed over the suction plate and can be carried mechanically, driven by a motor. The gap (*d*) between the two inclined plates and the slit width of the suction plate are each 0.5 mm and the width of the perforated weave is 10 mm. The speed of the perforated weave was 2 mm/s. Figure 3(c) shows the actual device for the feasibility test.

3.2.2 Test results & discussion

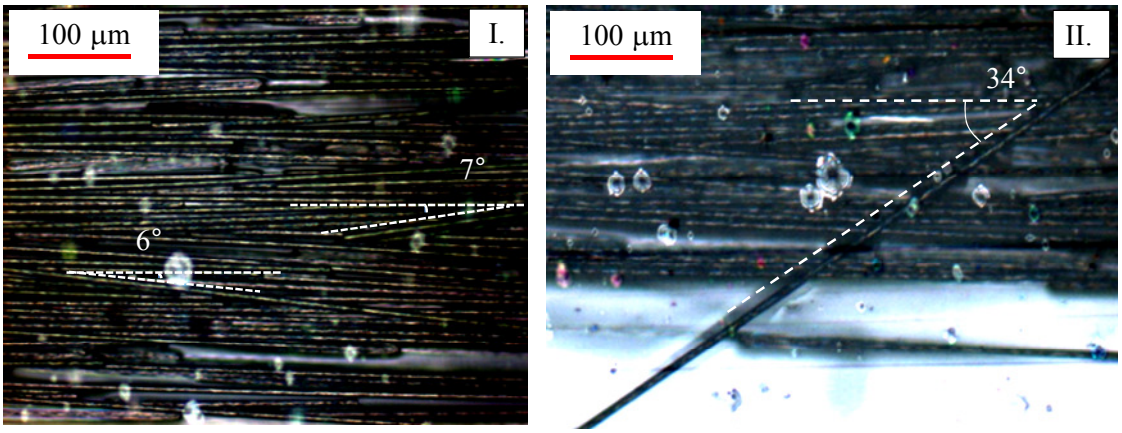
An aligned tow type preform was obtained in the feasibility test and the dimensions of the sample are 150 mm (l) × 0.5 mm (w) × 50 μm (t). Figure 4(a) and (b) show the top and side views of the sample and the experimental equipment, respectively, referring to Figure 3(b). During the test, fibre blockage did not occur at the end of the orientation head and fibres did not remain at the orientation head walls after the test.



(a) (b)

Figure 4. (a) Top view and (b) side view of the sample and device.

(a)



(b) (c)

Figure 5. (a), (b), (c) Microscope images of the aligned tow type preform sample with various magnifications.

Images of the sample were taken with a Carl Zeiss Jenavert microscope (Carl Zeiss, Bulgaria) to assess the fibre orientation as shown in Figure 5. Figure 5(a) shows the image of an aligned tow type preform of 7 mm length in the z-direction. Most of the fibres are aligned in region I, however some fibres are misaligned as shown in region II. There are two misalignment mechanisms. The first occurs as the fibres travel from the orientation head toward the perforated weave. When the over pressure of the water jet is applied to the orientation head, fibres, especially the first deposited, may rotate in the x-z plane because the orientation head and the suction plate are separated by a narrow gap so that the perforated weave can pass

between them. This mechanism can result in high levels of misalignment (34°, see the region II of Figure 5 (c)). Minimizing the gap between the orientation head and the suction plate and optimizing the velocity of the water (fibre suspension) jet can compensate for this misalignment. The other opportunity for misalignment occurs due to the geometry of the exit from the orientation head (d = 0.5 mm). A maximum misalignment of ±10° for 3 mm long fibres is expected, however the high packing condition of the fibres can reduce this geometry misalignment effect. The orientation distribution has been measured by photographing the preform in region I in Figure 5(a). The resulting image was imported into CAD software whereupon centre lines for each of the fibres were drawn over the images manually to an accuracy of ±0.5°. A text file containing details of the line orientations was exported to allow further processing. As a result, it was found that 80% of fibres were oriented within ±3° as shown in the probability density function created by the EasyFit software, Figure 6. The novel discontinuous fibre alignment method has therefore the potential to create discontinuous tow type preforms with high fibre alignment.

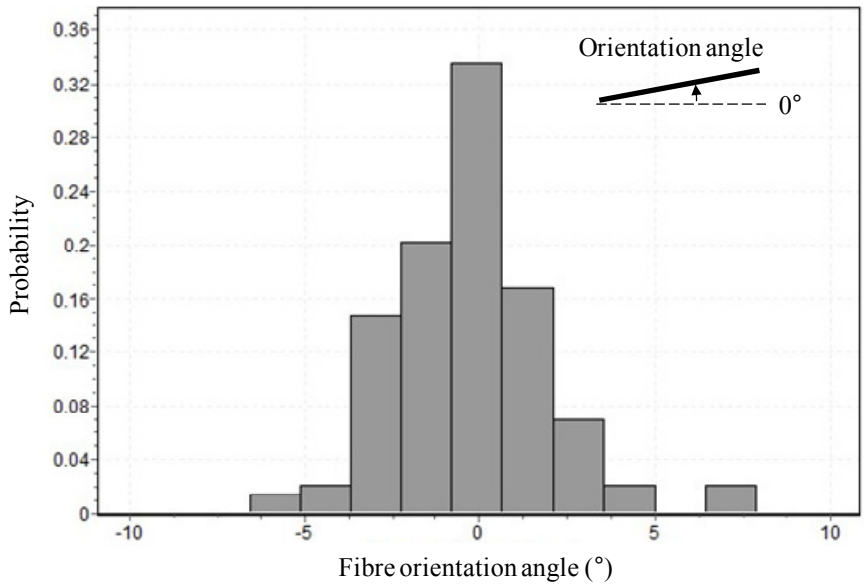


Figure 6. Probability density function for in-plane fibre orientations.

4 Conclusion & future work

In this paper, the limitations of conventional flow-induced discontinuous fibre alignment methods were investigated with Axiomatic Design theory. Conventional methods consist of 3 major steps: dispersing fibres, aligning fibres, and removing the carrier from the fibre suspension. Fibres are typically suspended in a highly viscous liquid such as glycerine to achieve the alignment by accelerating the carrier liquid through a converging nozzle or channel, forcing the fibres to follow the fluid streamlines. However, the high viscosity of liquid can be a main factor decreasing the productivity. It turns out to be a coupled design.

As a novel way of solving these problems, a method having a different orientation mechanism is proposed. The new discontinuous fibre alignment method uses a low viscosity medium such as water to disperse the fibres. The water (fibre suspension) jet flows into the orientation plates and then fibres are aligned perpendicularly to the water jet direction by hitting the inclined plate. This gives a fast and continuous process with highly aligned tow type preforms. A feasibility test was performed to verify the design concept, and a tow type preform with high orientation was obtained (80% fibres in the range of ±3°).

In the future, the extent of fibre orientation of samples will be assessed experimentally according to the fibre length, the fibre suspension jet flow velocity and the fibre volume

fraction of the suspension. Furthermore, tow type and tape type composites with discontinuous architecture will be manufactured using this novel method for assessment of performance.

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