A COMPARATIVE ANALYSIS OF DRILLING PROCESS PARAMETERS FOR SMALL AND LARGE HOLES IN JUTE REINFORCED POLYESTER COMPOSITES USING BOX-BEHNKEN DESIGN

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ABSTRACT: The present work evaluates how selected levels of the drilling parameters contribute to the delamination in drilling natural fibre-reinforced composites, specifically small and large holes. The jute/ unsaturated polyester composites were fabricated through a combination of vacuum bagging and hot compression moulding using 40 vol. % woven jute fabric. The primary effects and interactions on delamination due to feed rate (20 – 100 mm/min), spindle speed (500 – 1500rpm) and drill tool diameter (small bits of 4 – 8 mm and large bits of 20 – 30 mm) were organized using Response Surface Methodology (RSM) and Box Behnken design. The optimal drilling parameters for the smallest delamination factor at feed rate of 60.00 mm/min, spindle speed (1000.00 rpm) and drill diameter (6.00 mm). For the larger hole, the delamination factor is at the lowest when using a feed rate of 30.00 mm/min, spindle speed of 700.00rpm and drill diameter of 20.00 mm. The outcomes revealed that the feed rate and spindle speed are the most critical factors in the delamination of jute/ unsaturated polyester composite during the drilling process.

KEYWORDS: *jute fibre, drilling parameters, delamination factor, RSM, drill-bits diameters, Box-Behnken.*

1.0 INTRODUCTION

Jute fibre is among the most favourable natural fibres as a potential substitute for synthetic reinforcements, primarily due to its excellent mechanical characteristics, biodegradability, cost-effectiveness, low density, and sustainability, especially when evaluated in terms of cost-to-performance efficiency [1].

Machining fibre-reinforced composite materials presents significant challenges due to their heterogeneous structure, anisotropic behaviour and the high abrasiveness of reinforcing fibres [2-3]. In particular, natural fibre composites are prone to several machining-related defects during drillings such as delamination, fibre pull-out, hole shrinkage, spalling, fuzzing and thermal degradation. Numerous studies reported that conventional drilling and milling of these materials often lead to damage manifestations such as delamination, micro crackling, fibre debonding and thermal deterioration of the matrix [4-6].

While advanced machining techniques such as laser and waterjet cutting have been extensively applied to synthetic fibre-reinforced composites [5], conventional drilling using solid cutting tools continues to be the most commonly employed method due to its economic advantages and operational simplicity. Given the analogous fabrication processes shared by jute fibre composites and synthetic counterparts, it is postulated that natural fibre composites may exhibit comparable drilling-induced damage. Such damage is usually predominantly governed by the selection of machining parameters, the design of the cutting tool as well as the material's inherent characteristics [6-7].

Among these, delamination is one of the most common damage occurred. It is one of the most critical forms of damage encountered during machining operations, particularly in the drilling process. Delamination may compromise the structural integrity of the composite by weakening the interlaminar bonding in the machined section. Literature has shown that the initiation and propagation of the delamination are largely governed by the interaction between cutting tools and the anisotropic, heterogeneous nature of the composite materials [8].

The delamination defect from the drilling process can be observed at both the entry and exit regions of the hole. The primary factors contributing to this damage are widely acknowledged to be the cutting tool geometry and selected machining parameters, which significantly influence the severity of delamination and the quality of the hole produced [9-10]. It has been well recorded that the thrust force, which is largely a function of feed rate and tool geometry, is the main cause of delamination during the drilling of laminated composites [11]. Unanimously, the study of the parameters in inducing the delamination by drilling is the feed rate, spindle speed and the diameter of the drilling tool [6]. Furthermore, the specific characteristics of the drilling tools such as point angle, type of tooling materials, and number of flutes used are critical in influencing the onset and severity of the delamination during the drilling process [12].

Therefore, it is crucial to compare the optimum drilling parameters for the jute fibre/unsaturated polyester laminated composite between small and large drill bits. This study aims to ascertain the optimal combination of feed rates, spindle speeds, and drill bit diameters to minimise delamination and mitigate drilling-induced failures. A comparative analysis will be conducted to evaluate how variations in drill bit size influence the relationship among these machining parameters. The parameters proposed in this study are key factors due to their significant impact on delamination in drilled composite laminates [13]. Drilling the laminate is complex and requires specific consideration of the relationship between drill bit geometry and wear resistance. Tool geometry, such as the flute variant, also plays a crucial role in reducing the delamination effect. Thus, this study intends to establish correlations among these drilling parameters, particularly when used in natural fibre-based composites, using Response Surface Methodology (RSM) with Box-Behnken design.

2.0 METHODOLOGY

2.1 Materials

The jute fibre (Biotex-Jute™) used in this study is supplied Composite Evaluation (UK) in the form of woven mat and light brown colour. The matrix materials are unsaturated polyester resin (PCCR 733-6544), and methyl ethyl ketone peroxide (MEKP) as curing agent, both supplied by Revertex Sdn. Bhd, and their details are shown in Table 1.

Table 1: Physical, mechanical, and thermal properties of raw materials

Properties	Jute	Polyester
Density	1.3 g/cm3	1.09 g/cm3
Tensile strength	393 MPa	40 MPa
Melting point	230°C	54°C

2.2 Composite Fabrication

The jute fibres were treated with 5% NaOH solution for 30 min. The jute mat was manually placed into a 300mm x 300mm x 3mm mould at 40 vol.% (v/v). The unsaturated polyester resin was combined with MEKP hardener per the manufacturer's recommendations. The mixture and then poured into the mould and vacuum bagged for 2 hours. Afterwards, the mould was hot compressed temperature of 168 °C for 20 minutes under a pressure of 3.5 MPa as detailed in our previous study [14].

2.3 Drilling Process

The drilling process on the jute/unsaturated polyester composite was carried out using a computer numerical control (CNC) MAHO vertical machining centre (Model XD-40A) (Figure 1). The machine was equipped with spindle speed with a capacity of up to 5000 rpm and a workable (1270 x254mm). the experiment utilized standard high-speed steel (HSS) twist drill bits supplied by Sandvik (Germany) with diameters of 4mm, 6mm and 8 mm (small-size tools) and 20 mm, 25 mm and 30 mm bits (large-size tools). A G-code program was developed to automate the drilling process, with each experimental run involving the drilling of five holes under varying parameter settings. The primary process parameters employed are feed rate (mm/min), spindle speed (RPM) and drill bit diameters (mm).

Post-drilling, delamination around the holes was assessed using the SRF Microscopy system, and the corresponding measurements were systematically recorded.

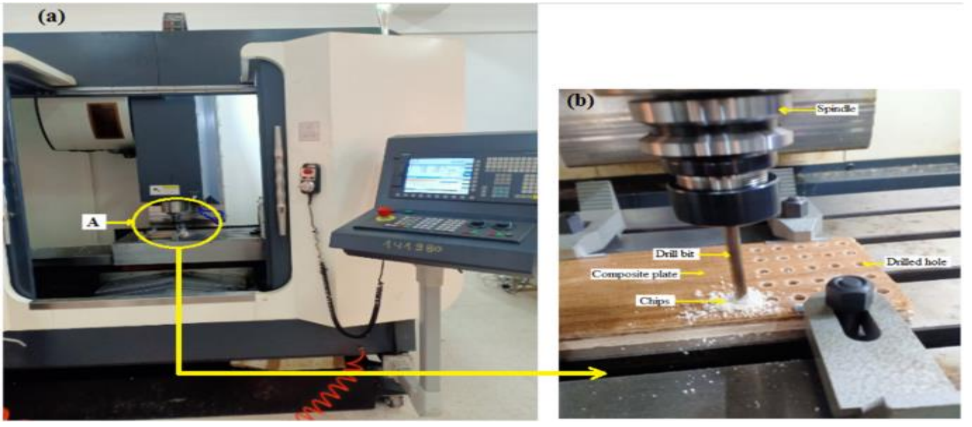


Figure 1: Drilling experiment set up (a) fixed on vice in the CNC Machine (b) drilling number of holes based on parameters

2.4 Delamination factor

The delamination is often found both at the hole entry and hole exit. The entry region is caused by the peel-up force from the cutting tool while the exit region is caused by the push-out force [15]. The delamination factor around the holes, and the maximum diameter (*Dmax*) in the delamination zone were measured as shown in Figure 2. The delamination factor (*Fd*) can be calculated using Equation (1)

$$F_d = \frac{D_{max}}{d} \quad (1)$$

Where *Dmax* is the maximum diameter of the delamination region (mm) and *d* denotes the nominal diameter of the drill-bit (mm). thus, the delamination factor approaching or equal to *Fd* =1.00, indicating an ideal drilling outcome where a minimal delamination relative to the drill size.

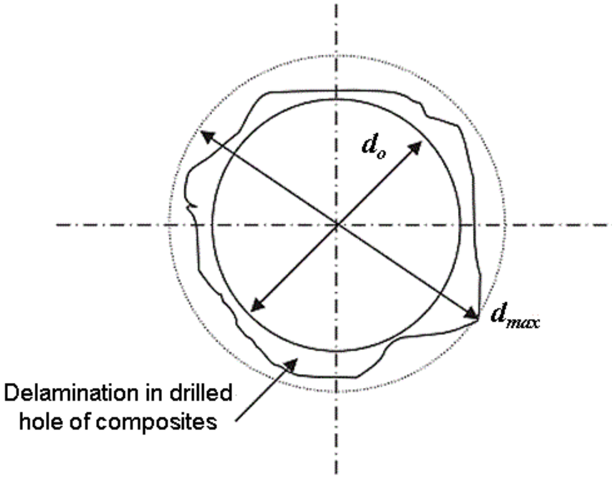


Figure 2: Schematic diagram of drilling-induced delamination diameter, d, in composites [16].

2.4 Design of Experiment

The correlation of the selected drilling process parameters was analysed using Response Surface Methodology (RSM), and Box-Behnken design (BBD) for the experimental layout. This design enables efficient evaluation of the interactions among the variables while minimizing the number of required experimental runs. The key parameters investigated included feed rate, spindle speed and drill bit diameters using three levels of conditions as detailed in Table 2. A total of 17 experiments with 3 replications for the optimization process (Tables 3 and 4).

Table 2: Physical, mechanical, and thermal properties of raw materials

Process parameters	Levels		
	+ 1 level	0 level	−1 level
Feed Rate (mm/min)	20	60	100
Spindle Speed (rpm)	500	1000	1500
Small Tool Diameter (mm)	4	6	8
Large Tool Diameter (mm)	20	25	30

Table 3: Three-factor Box-Behnken design experiment with predicted response of dependent variable (delamination factor) for small size tool diameter

Runs	Factor 1 A: Feed Rate (mm/min)	Factor 2 B: Spindle Speed (rpm)	Factor 3 C: Tool Diameter (mm)
1	60.00	1000.00	6.00
2	20.00	1500.00	6.00
3	60.00	1000.00	6.00
4	60.00	1500.00	4.00
5	20.00	500.00	6.00
6	20.00	1000.00	8.00
7	100.00	500.00	6.00
8	20.00	1000.00	4.00
9	60.00	1500.00	8.00
10	60.00	1000.00	6.00
11	100.00	1000.00	8.00
12	100.00	1500.00	6.00
13	60.00	1000.00	6.00
14	60.00	500.00	8.00
15	60.00	500.00	4.00
16	60.00	1000.00	6.00
17	100.00	1000.00	4.00

Table 4: Three-factor Box-Behnken design experiment with predicted response of dependent variables (delamination factor) for large-size tool diameter

Runs	Factor 1 A: Feed Rate (mm/min)	Factor 2 B: Spindle Speed (rpm)	Factor 3 C: Tool Diameter (mm)
1	20.00	1500.00	25.00
2	60.00	1000.00	25.00
3	100.00	1000.00	30.00
4	100.00	1500.00	25.00
5	20.00	500.00	25.00
6	60.00	1500.00	20.00
7	60.00	1000.00	25.00
8	100.00	1000.00	20.00
9	60.00	1000.00	25.00
10	20.00	1000.00	30.00
11	60.00	1000.00	25.00

12	60.00	1000.00	25.00
13	60.00	500.00	20.00
14	60.00	1500.00	30.00
15	20.00	1000.00	20.00
16	60.00	500.00	30.00
17	100.00	500.00	25.00

2.5 Statistical analysis

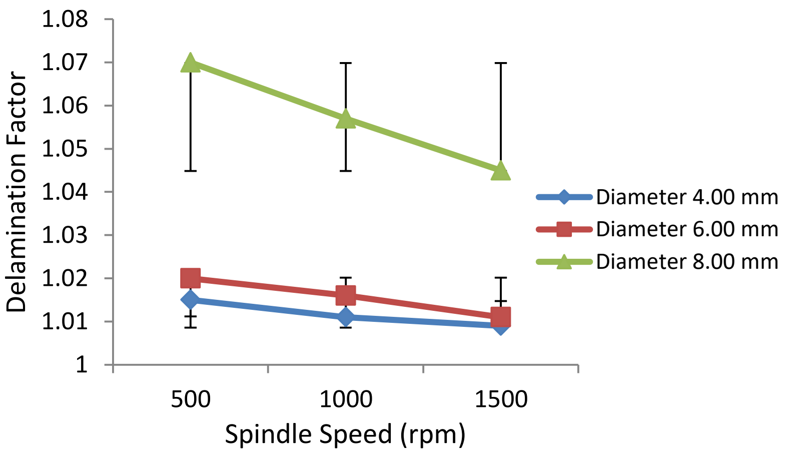
The significance of the drilling process parameters on the flexural properties of the jute fibre/unsaturated polyester laminated composites was evaluated using Analysis of Variance (ANOVA). A cubic regression model was employed to examine both of the main effects and their interactions, with the delamination factor serving as the response variable. The statistical analysis and model fitting were conducted using Design Expert 9 software (Star-ease Inc., USA) which is capable of generating a dimensional response surface plot for visualizing the interaction effects. To assess the adequacy and predictive capability of the regression model, the multiple correlation coefficient (R) and the coefficient of determination (R^2) were computed [17]. Furthermore, point prediction optimisation was performed to determine the optimal levels of each process parameter that minimises the delamination factor.

3.0 RESULTS AND DISCUSSION

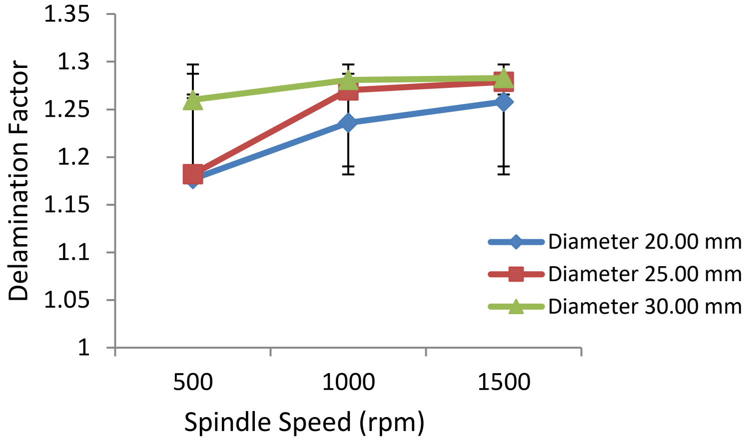
3.1 Effect of drilling process parameters on delamination factor

The influence of drilling parameters on the delamination factor during the machining of jute fibre/unsaturated composites is illustrated by plotting the delamination factor against spindle speed (Figures 3 and 4). The corresponding relationship between drill bit diameter and spindle speed for small diameters is given in Figure 3a. The result reveals that an increase in drill diameters leads to a corresponding rise in the delamination factors, thus producing greater damage. Conversely, higher spindle speeds show a reduction in delamination factors, suggesting improved hole quality under these conditions. Our preliminary study [18] shows that as the drill tool diameter increases, the load on the tool and contact between the workpiece and tool increase which results in more delamination. On another hand, the increase of spindle speed may soften the matrix material thus enabling the removal of the composite with ease and hence the delamination is reduced.

Figure 3b shows that when a larger size drill diameter is used, the delamination increases slightly for every increment of drill size. However, the delamination ratio effect becomes constant regardless of the drill size at higher spindled speed (from 1000 -1500 rpm). Typically, when larger diameter tools are used, it will produce large delamination because of the bigger load and thrust force. However, higher spindle speeds will result in decreased delamination due to the higher heat generation and mechanical stresses, which weaken the fibre-matrix interface making it easier to be drilled [6].



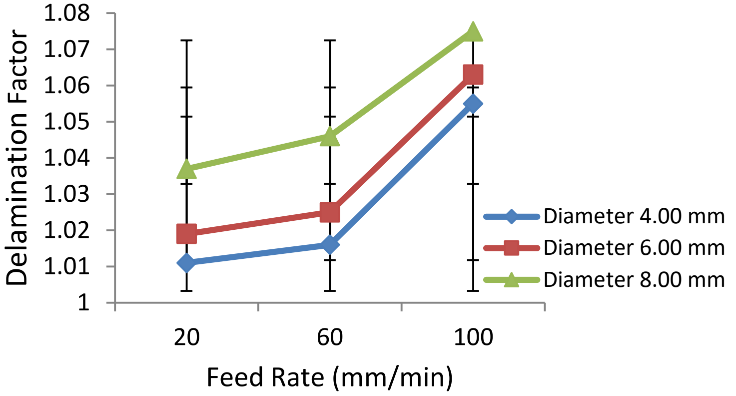
(a)



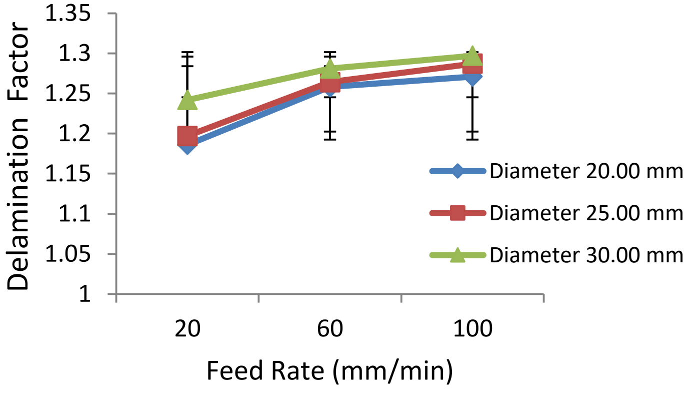
(b)

Figure 3: Effect of drill diameter and spindle speed on delamination factor with different drill bit sizes (a) 4-8 mm and (b) 20-30 mm

Figure 4 shows the effect of drill tool diameter for different feed rates on the delamination factor in the drilling of composite materials. As shown in Figure 4a, an increase in feed rates leads to a noticeable rise in the delamination factor, indicating greater damage. Drill bit diameters are identified as critical parameters affecting drilling performance. Bigger drill diameters combined with higher feed rates increase the tool-workpiece interaction area and mechanical load that is applied during the cutting, which intensifies delamination. These observations underscore the importance of optimising drilling parameters to effectively minimise delamination and enhance the overall quality of drilled holes in composite laminates. It was also observed in larger drill bit diameters, that the delamination ratio becomes constant when a drilling feed rate above 80 mm/min is used (Figure 4b). This is due to the increased stability and reduced relative motion between the tool and the composite material [6].



(a)



(b)

Figure 4: Effect of drill diameter and the feed rate on the delamination factor

3.1 Optimisation of the delamination factor in the drilling of jute/unsaturated composite

The most effective approach to optimise drilling parameters is by using a three-dimensional Response Surface Model (RSM) which is capable provide insight interaction of each factor used. this enables a comprehensive evaluation of how the feed rate, spindle speed and drill bit diameters impact the delamination factors. Figure 5 presents the 3D response in a contour plot of the interaction effect between feed rate and spindle speed while tool diameters are kept constant. The result shows that in small diameter drill bits (Figure 5a) an optimal delamination factor (1.00) can be achieved by operating the spindle speed within the range of 750 to 1500 rpm and maintaining a low feed rate between 20.00 mm/min and 70.00 mm/min. In contrast, when the feed rate is elevated to 100.00 mm/min, the delamination factor deviates from the desired range, even at a lower spindle around 500 rpm. The optimal zone for minimizing delamination is visually represented in the dark blue region of the surface plot, indicating favourable parameter combinations.

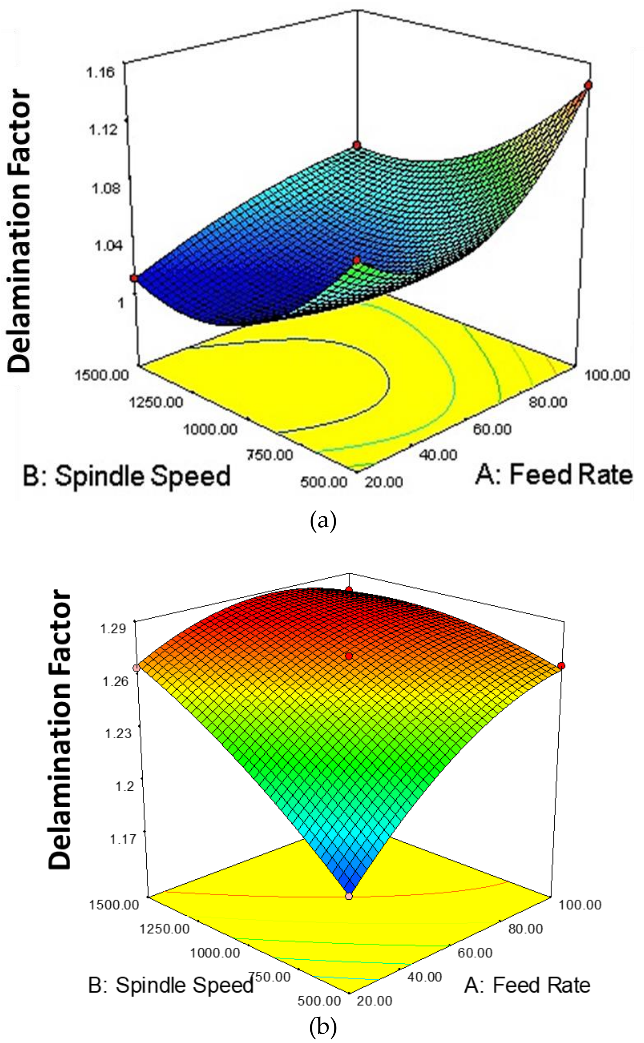


Figure 5: 3D response surface plot of delamination factor; (a) small diameter tools (b) large diameter tools

Figure 5b shows the RSM contour plot of the interaction between feed rate and spindle speed using large-diameter drill bits. The surface analysis demonstrates that the optimal drilling conditions with a delamination factor of 1.00 are achieved when the spindle speed range of 500 to 700 rpm was used, combined with a low feed rate between 20.00mm/min and 30.00 mm/min. The plot further suggested that increasing the spindle speed to 1000 rpm while applying a higher feed rate of 60.00 mm/min will result in a delamination factor that deviates from the desired range, emphasising the need for careful parameter control to minimise drilling-induced damage.

4.0 CONCLUSION

The influence of drilling process parameters using both small (4 mm - 8 mm) and large (20 mm - 30 mm) diameter drill bits on the delamination factor of jute fibre/ unsaturated polyester laminated composite was experimentally investigated. The results demonstrate that the feed rate and spindle speed are the most critical factors affecting the extent of delamination formation in the composite materials.

In conclusion:

i. The application of 3D-RSM coupled with contour plots has proven effective in optimizing the selected drilling parameters (feed date, spindle speed and tool diameters) to achieve minimal delamination.

ii. The delamination factor is significantly affected by variations in feed rate, spindle speed, and drill bit diameters, with higher feed rates and larger diameters generally resulting in increased delamination.

iii. For small-diameter drill bits, the optimal parameter combination that yields the smallest delamination factor of 1.025 was achieved with a feed rate of 60.00 mm/min, a spindle speed of 1000.00 rpm, and a drill diameter of 6.00 mm.

iv. For large-diameter drill bits, the minimum observed delamination factor of 1.197 was achieved at a feed rate of 30.00 mm/min, a spindle speed of 700.00 rpm and a drill diameter of 20.00mm.

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AUTHOR CONTRIBUTIONS

N.H. Idrus: Conceptualization, Methodology, Software, Formal analysis Writing- Original Draft Preparation; Z. Mustafa: Data Curation, Validation, Supervision; S.H.S.M. Fadzullah: Writing-Review and Editing; K. Thongkaew: Writing-Review and Editing, data validation, L.F. Ng: Writing-Review and Editing; A.R. Aziz: Writing-Review and Editing

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest in the manuscript.

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