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INNOVATIVE APPROACH TO SPECIFIC CUTTING COEFFICIENT ESTIMATION FOR A HYBRID POLYESTER COMPOSITE WITH RUBBER AND FIBERGLASS

M. Mosaad, T. S. Mahmoud, Ibrahim Mousa, S. S. Mohamed

Mechanical Engineering Department - Faculty of Engineering at Shoubra, Benha University, El Sahel, 11614, Cairo, Egypt

*Correspondence: mohamed.atia18@feng.bu.edu.eg

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ABSTRACT

This study proposes a novel methodology for predicting specific cutting coefficients in a hybrid polyester composite reinforced with rubber and fiberglass. Composite materials, notably fiber-reinforced polymers, are widely used in various industries, including yachting, automotive, and aviation. Glass fiber-reinforced polyester is a common example. To reduce costs and improve impact resistance, waste tire rubber particles are often added to these composites. Experimental investigations were conducted to evaluate the effects of cutting parameters, including feed rate and depth of cut, on the specific cutting coefficient. Results indicate that incorporating rubber particles into the composite matrix significantly lowers the specific cutting coefficient compared to composites reinforced exclusively with fiberglass. This reduction is attributed to the rubber's inherent ability to absorb and dissipate energy during the cutting process. Additionally, the study demonstrates a general trend of decreasing specific cutting resistance with increasing feed rates, primarily due to the formation of larger shear zones and enhanced heat dissipation. However, excessive feed rates can adversely affect tool life and surface quality. The findings of this research offer valuable insights for optimising machining operations involving hybrid polyester composites and contribute to advancements in composite materials processing technology.

KEYWORDS: Cutting Parameters, Specific Cutting Coefficient, Polyester-Fiberglass Composites, Waste Tire Rubber Particles, Drilling Operation

تقديرمعامل القطع النوعي لمادة مركبة هجينة من البوليستر المطاط والألياف الزجاجية

محـمد مسعد فتحي عطيه، تـامر سـمير مـحمود، إبـراهـيم موسـى إبـراهـيم، سـماح سمير محمد

قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بنها، الساحل،11614، القاهرة، مصر.

***البريد الاليكتروني للباحث الرئيسي :** mohamed.atia18@feng.bu.edu.eg

الملخص

تهتم هذه الدراسة بتقدير معامل القطع النوعي في مادة مركبة هجينة من البوليستر المقوى بالمطاط والألياف الزجاجية. تم إجراء تحقيقات تجريبية لتقييم تأثيرات معاملات القطع، بما في ذلك معدل التغذية وعمق القطع، على القوة النوعية للقطع. تشير النتائج إلى أن دمج جزيئات المطاط في مصفوفة المركب يقلل بشكل كبير من معامل القطع النوعي مقارنة بالمركبات المقواة بالألياف الزجاجية فقط. يعزى هذا الانخفاض إلى قدرة المطاط الفطرية على امتصاص الطاقة وتبديدها أثناء عملية 58القطع. بالإضافة إلى ذلك، توضح الدراسة اتجاهًا عامًا لانخفاض المقاومة النوعية للقطع مع زيادة معدلات التغذية، وذلك بشكل أساسي بسبب تكوين مناطق القص الأكبر وتحسين تبديد الحرارة. ومع ذلك، يمكن أن تؤثر معدلات التغذية المفرطة سلبًا على عمر الأداة وجودة السطح. تقدم نتائج هذه الدراسة رؤى قيمة لتحسين عمليات التصنيع باستخدام مواد مركبة هجينة من البوليستر والمساهمة في التطورات في مجال معالجة المواد المركبة.

الكلمات المفتاحية : معاملات القطع ، القوة النوعية للقطع ، مركبات البوليستر و الالياف زجاجية ، جزيئات مطاط الإطارات المستعملة، عمليه الثقب.

1. INTRODUCTION

A pressing need exists to minimize energy consumption and environmental impact in manufacturing processes [1]. This necessitates the development of sustainable materials and manufacturing techniques that optimize material efficiency and reduce ecological footprint. The adoption of novel or modified materials and processes for specific applications hinges on fulfilling a multitude of criteria, including production costs, recyclability, and machinability [2]. Polyester composites are renowned for their exceptional strength-to-weight ratio, making them ideal for applications where weight reduction is paramount, such as aerospace and automotive components. Their versatility in design, facilitated by their malleability, enables the creation of intricate and functional structures. Moreover, polyester composites offer a compelling balance of mechanical properties and affordability, making them a practical choice for a wide range of engineering applications [3].

The E-glass fibers, serving as the reinforcement, impart exceptional tensile strength, stiffness, and dimensional stability to the composite. The polyester resin, acting as a binding matrix, effectively encapsulates the fibers, enhancing their mechanical properties and imparting corrosion resistance, chemical inertness, and dielectric properties. This synergistic combination results in a composite with superior overall performance [4].

Waste tire particles offer a sustainable and economically viable alternative as a reinforcement material for polyester composites. To fully realize their potential, it is imperative to address compatibility and dispersion challenges between the waste tire particles and the polyester matrix. Ongoing research and development efforts are essential to expand the application of waste tire particles in a diverse range of composite materials [5], [6].

Conventional drilling remains the predominant method for processing composite laminates due to its efficiency and cost-effectiveness. However, the drilling process can introduce various types of damage within the composite structure. Microscopic cracks and debonding between layers can occur, along with macroscopic delamination, which involves the separation of individual laminate layers. These forms of damage can significantly compromise the structural integrity of the composite material [7], [8].

In the realm of drilling operations, the specific cutting coefficient (Ks) emerges as a critical indicator of a material's machinability. This numerical value quantifies the force necessary to remove a unit volume of material during the drilling process. As a material-specific property, Ks reflects the intrinsic resistance of a substance to cutting. A lower Ks value signifies a more easily machinable material, requiring less force for drilling [9].

A material with a low Ks value offers several advantages in drilling. Reduced drilling power requirements contribute to lower energy consumption, while diminished tool wear extends the lifespan of the drill bit. Moreover, a cleaner hole quality can be achieved, minimizing the risk of damage to the surrounding material. To optimize drilling operations, understanding the Ks value of a material is essential. By judiciously selecting appropriate drill bit materials, geometries, cutting speeds, and feed rates, drilling efficiency can be maximized, and tool life can be prolonged [10].

While the Ks value provides valuable insights, it is not the sole determinant of drilling performance. Additional factors, such as the material's ductility or brittleness, the use of lubricants and coolants, and the drill bit's design, also influence the drilling process. A comprehensive consideration of these factors is necessary for achieving optimal results in various drilling applications [11].

During machining operations, the cutting force exerted on a tool during a specific chip section is directly influenced by the variation in cutting speed. This relationship can be attributed to the underlying changes in specific cutting force, a fundamental parameter that quantifies the force required to remove a unit volume of material [12].

The effects of drilling parameters on thrust force, torque, and delamination in glass fiber reinforced plastic (GFRP) composites were examined. Their findings confirmed the established trend of increasing thrust force and torque with higher feed rates. Additionally, the study provided quantitative data specific to the GFRP materials used. A positive correlation was observed between fiber volume fraction and both thrust force and torque. In contrast, increasing cutting speed resulted in a decrease in these forces. The study also revealed a correlation between increased feed rate and larger delamination size. Push-out delamination was found to be more prevalent than peel-up delamination. While cutting speed had a minimal impact on delamination size, achieving delamination-free drilling in chopped GFRPs with high fiber volume fraction remains a challenge [13].

Investigation by [14], The use of recycled waste tire rubber as a reinforcement material in polyester-fiberglass composites. The study employed a factorial design to optimize the mesh size and rubber content for enhanced mechanical and dynamic properties. Results showed that both factors significantly influenced the composite's performance, with optimal combinations leading to improved tensile strength, strain, impact resistance, natural frequency, and damping factor. This research demonstrates the potential of waste tire rubber to create sustainable and high-performance composite materials.

A study was conducted to investigate the drilling performance of a composite material at high speeds. The findings revealed a direct correlation between an increase in cutting velocity and a corresponding rise in drill wear. This observation highlights the significant impact of cutting velocity on tool life and performance in the context of drilling composite materials. [15].

Comparing a novel laminated polyester composite incorporating waste tire rubber particles and glass fibers to traditional glass fiber-reinforced composites containing calcium carbonate ($CaCO_3$) was done by [16]. The novel composite holds potential applications in the automotive and aviation sectors. Flat laminated specimens of both the innovative and conventional composites were fabricated using a hand layup technique. The findings revealed an approximate 47% improvement in the novel composite, accompanied by an 8% reduction in density. Additionally, an optimal drilling speed of around 1150 rpm was identified to minimize delamination on both the front and back faces of the specimens.

The specific cutting force was found to decrease with both cutting velocity and feed. The Viapal VUP 9731 matrix exhibited lower specific cutting force than the ATLAC 382-05 under identical cutting conditions. Feed was determined to have a more significant impact on the specific cutting force, contributing to 99.1% and 91.6% of the variation for the two composite materials, respectively. Delamination increased with both cutting parameters, but the "Brad&Spur" drill caused less damage to the Viapal VUP 9731 matrix compared to the ATLAC 382-05. Feed was also the primary factor influencing the delamination factor, accounting for 63.5% and 72.8% of the variation in the two composites. Surface roughness increased with feed but decreased with cutting velocity. Cutting speed had the most substantial influence on surface roughness for both composite materials, contributing to 77.2% and 65.5% of the variation, respectively [17].

The research investigates the cutting forces in helical milling by [18], focusing on the impact of cutting parameters on cutting force coefficients. The study proposes both linear and nonlinear cutting force models to simulate the cutting process. By analyzing experimental data, the researchers identified cutting force coefficients for both models and compared their accuracy. The results highlight the importance of considering the relationship between cutting force coefficients and cutting parameters for accurate cutting force prediction. This research contributes to a deeper understanding of the cutting process and can aid in optimizing machining parameters.

2. Materials and Methods

The materials employed in this research included unsaturated polyester resin, recycled rubber particles, and fiberglass. The polyester resin, procured from SUNPOL in Turkey, exhibited a density of 1.23 g/cm³. Recycled rubber particles, measuring 40 mesh (0.420 mm), were sourced from HOPPEC in Egypt and added to the composite in a volume percentage of 10%, These particles displayed an average density of 0.4 g/cm³. Fiberglass, designated as product number E01, was supplied by the Jushi Chinese-Egyptian company.

Composite laminates were fabricated utilizing a hand lay-up technique, a well-established method for producing customized composite components. [19]. This process entailed constructing a silicone rubber mould conforming to standard dimensions for specimens. The polyester resin was subsequently mixed with a hardener and subjected to a degassing process before being poured into the mould for curing. To incorporate rubber particles, the resin mixture was prepared anew, with the particles added prior to the curing phase. Finally, the fiberglass was strategically positioned within the mould, and the resin mixture was applied to create the desired composite structure [20].

A benchtop drill, model PMC-40 from Bulgaria, with a maximum speed of 2400 rpm was employed to create holes in the composite. A feed rate of 0.11 and 0.22 mm/rev was maintained throughout the drilling process. High-speed steel (HSS) drills, manufactured by the Spanish company IZAR Cutting Tools, with diameters of 4, 6 and 8 mm, were utilized for all drilling operations. The drilling force was measured using a Dynamometer V-TECH DIGITAL FORCE INDICATOR MODEL 252 to evaluate the impact of varying drilling parameters on the resulting force.

3. Results and Discussion

The specific cutting coefficient, denoted as Ks, is typically expressed in units of mega Pascal's (MPa). To calculate Ks, a mathematical expression involving the cutting torque (M) (M=f*D/2), feed rate (f), and drill diameter (d) is employed. The equation, presented below, provides a quantitative framework for determining Ks:

$$K_s = \frac{8 * M}{f * d^2}$$

3.1 Specific cutting coefficient of polyester matrix resin

To determine the Ks, drilling experiments were conducted on polyester resin samples. The following Table 1 presents the data collected during these operations.

The influence of drill diameter and feed rate on the drilling process of polyester resin employing a high-speed steel drill bit was investigated. Data were gathered for three drill diameters (4 mm, 6 mm, and 8 mm) and two feed rates (0.11 mm/rev and 0.22 mm/rev). The primary parameters measured included force, torque, and specific cutting force (Ks). Analysis of the data indicated a direct relationship between drill diameter and the requisite force and torque. Larger drill diameters demand greater force and torque to remove the increased volume of material. Moreover, while increasing the feed rate generally resulted in higher force and torque, the specific cutting force, which signifies the efficiency of material removal, displayed a less pronounced change or even a slight decrease. This suggests that higher feed rates can enhance drilling efficiency [21].

Table 1: The drilling parameters data for the polyester resin samples

Dia. H.S.S	d^2 (mm^2	d/2 (mm)	feed (mm/rev)	Force (N)	Torque (M)(N.m)	Ks (MPa)
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.22	88.2	176.4	400.9091
4	16	2	0.11	58.8	117.6	534.5455
4	16	2	0.22	98	196	445.4545
4	16	2	0.22	49	98	222.7273
6	36	3	0.11	49	147	296.9697
6	36	3	0.11	49	147	296.9697
6	36	3	0.22	98	294	296.9697
6	36	3	0.11	68.6	205.8	415.7576
6	36	3	0.22	88.2	264.6	267.2727
6	36	3	0.22	49	147	148.4848
8	64	4	0.11	78.4	313.6	356.3636
8	64	4	0.11	78.4	313.6	356.3636
8	64	4	0.22	156.8	627.2	356.3636
8	64	4	0.11	58.8	235.2	267.2727
8	64	4	0.22	88.2	352.8	200.4545
8	64	4	0.22	78.4	313.6	178.1818

The calculated mean value of Ks for this experiment was 316.2727 N/mm². Figure 1 graphically illustrates the correlation between Ks and feed speed during the drilling process.

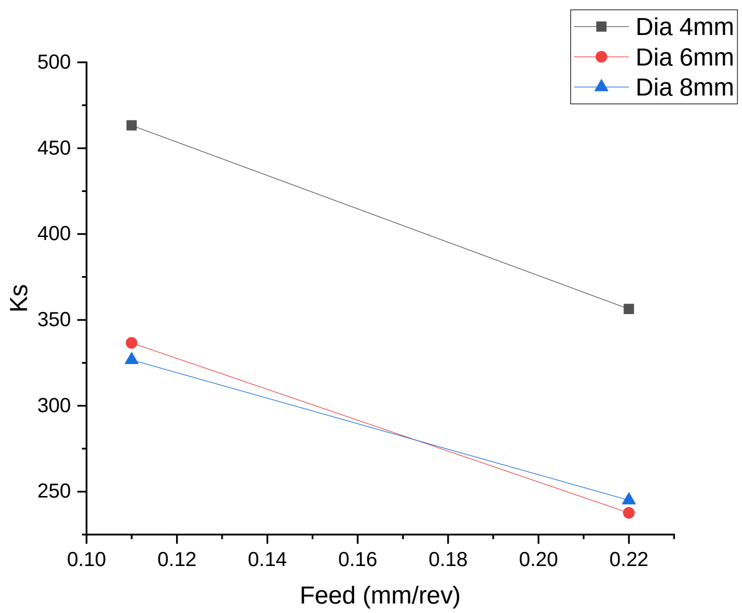

Figure 1: Analysis of specific cutting force (Ks) in polyester resin drilling as influenced by feed rate and twist drill diameter.

3.2 Specific cutting coefficient of polyester fiberglass laminates

As depicted in Table 2, a strong positive correlation exists between drill diameter and the requisite force and torque. This trend is exemplified by a significant uptick in both force and torque when the drill diameter is augmented from 4 mm to 8 mm, even at a constant feed rate. The increased material removal volume is a primary contributor to this phenomenon.

While elevating the feed rate generally results in higher force and torque values, the specific cutting force (Ks) exhibits a less pronounced change or even a slight decrease. This suggests that increasing the feed rate can enhance drilling efficiency. For instance, comparing the Ks values for a 6 mm drill at 0.11 mm/rev and 0.22 mm/rev, it is evident that the rise in force and torque is not commensurate with the increase in Ks, indicating improved efficiency.

Table 2: Characterization of polyester fiberglass composites through drilling operations

Dia. H.S.S	D2	d/2	feed (mm/rev)	Force (N)	Torque (N.mm^2)	Ks (N/mm^2)
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.22	88.2	176.4	400.9091
4	16	2	0.11	58.8	117.6	534.5455
4	16	2	0.22	88.2	176.4	400.9091
4	16	2	0.22	58.8	117.6	267.2727
6	36	3	0.11	49	147	296.9697
6	36	3	0.11	49	147	296.9697
6	36	3	0.22	88.2	264.6	267.2727
6	36	3	0.11	58.8	176.4	356.3636
6	36	3	0.22	88.2	264.6	267.2727
6	36	3	0.22	68.6	205.8	207.8788
8	64	4	0.11	68.6	274.4	311.8182
8	64	4	0.11	68.6	274.4	311.8182
8	64	4	0.22	107.8	431.2	245
8	64	4	0.11	78.4	313.6	356.3636
8	64	4	0.22	117.6	470.4	267.2727
8	64	4	0.22	117.6	470.4	267.2727
8	64	4	0.22	88.2	352.8	200.4545
8	64	4	0.22	78.4	313.6	178.1818

The mean specific cutting force (Ks) during the drilling of polyester fiberglass laminates was determined to be 341.1439 N/mm^2. The correlation between Ks and feed rate during the drilling process is visually represented in Figure 3.

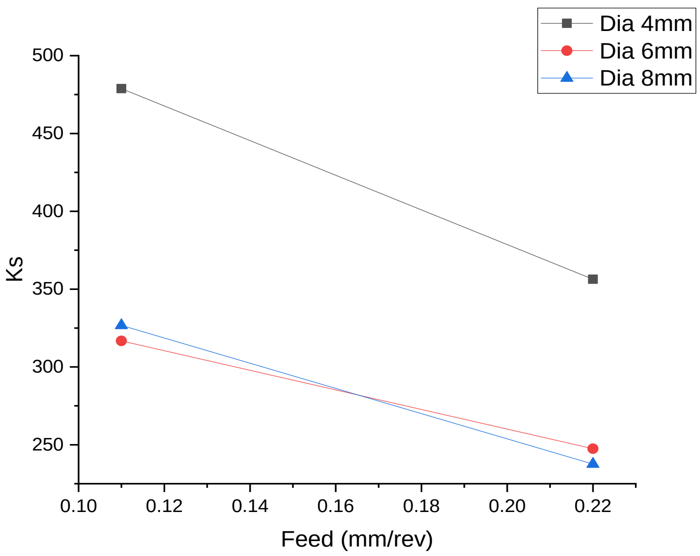

Figure 3: Specific cutting force as a function of feed rate and drill diameter for polyester fiberglass.

3.3 Specific cutting coefficient of polyester fiberglass with rubber particles laminates

The drilling data in Table 3 demonstrated a direct correlation between drill diameter and the required cutting forces and torques. As the drill diameter increased from 4 mm to 8 mm, a significant augmentation in both force and torque was observed, as evidenced by comparing the force values for identical feed rates. This trend is a direct consequence of the increased material removal volume associated with larger drill diameters.

An increase in feed rate generally led to higher cutting forces and torques, the specific cutting force (Ks) exhibited a less pronounced change or even a slight decrease, suggesting improved material removal efficiency at higher feed rates. For example, comparing the Ks values for a 6 mm drill operating at different feed rates, it is evident that the increase in force and torque is not proportional to the increase in Ks, indicating enhanced cutting efficiency [22].

Table 3: Drilling data for polyester fiber-reinforced resin samples containing rubber particles

Dia. H.S.S	D2	d/2	feed (mm/rev)	Force (N)	Torque	Ks
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.11	49	98	445.4545
4	16	2	0.22	68.6	137.2	311.8182
4	16	2	0.22	58.8	117.6	267.2727
6	36	3	0.11	49	147	296.9697
6	36	3	0.11	49	147	296.9697
6	36	3	0.11	49	147	296.9697
6	36	3	0.22	58.8	176.4	178.1818
6	36	3	0.22	68.6	205.8	207.8788
8	64	4	0.11	58.8	235.2	267.2727
8	64	4	0.11	58.8	235.2	267.2727
8	64	4	0.11	68.6	274.4	311.8182
8	64	4	0.22	107.8	431.2	245
8	64	4	0.22	98	392	222.7273

The mean specific cutting force (Ks) for the drilling operation was determined to be 300.4343 N/mm². Figure 3 illustrates the interdependence of drill diameter, feed rate, and Ks during the machining of a polyester-fiber composite reinforced with fiberglass and rubber particles. A trend of decreasing Ks with increasing drill diameter was observed, suggesting greater efficiency at larger diameters. Furthermore, higher feed rates correlated with lower Ks values, indicative of improved material removal. Nevertheless, the influence of feed rate on Ks was more pronounced for smaller drill diameters [23].

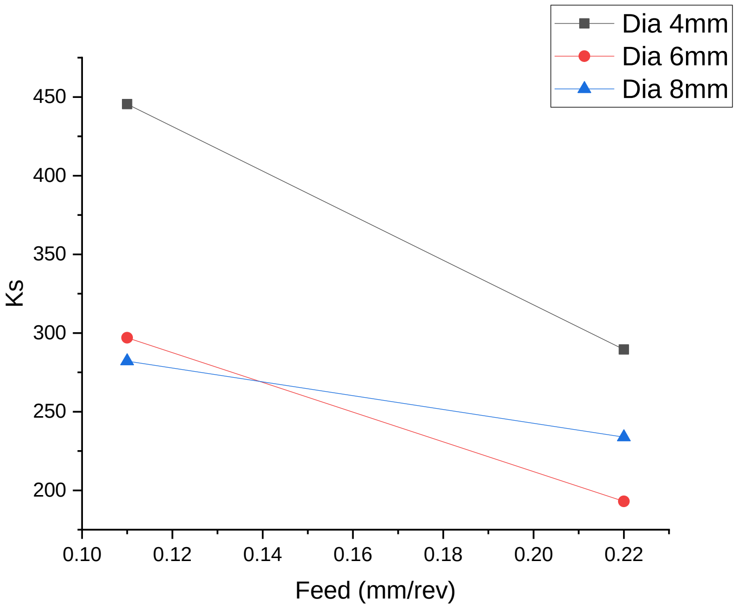

Figure 4: Influence of feed rate and drill diameter on the specific cutting force during the machining of polyester fiber-reinforced waste tire rubber.

In Figure 5 the comparison between different investigated materials at feed 0.22 mm/rev and drill diameter 6 mm.

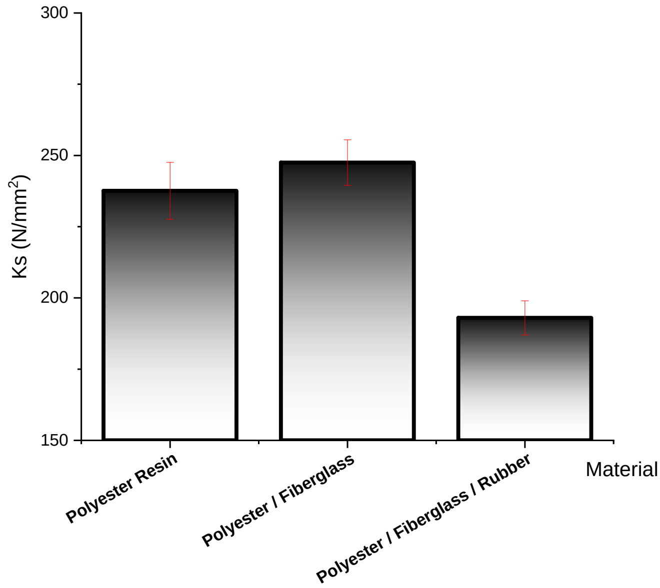

Figure 5: specific cutting force during the machining at feed rate 0.22 mm/rev and drill size 6 mm.

The addition of fiberglass to polyester resin increases its cutting-specific resistance due to its increased stiffness and abrasive nature. However, incorporating rubber particles into this mixture can counteract these effects, leading to a lower cutting-specific resistance. This is attributed to the reduced stiffness, improved chip formation, and reduced friction provided by the rubber particles. Consequently, the choice of reinforcement material significantly impacts the energy required for drilling polyester resin.

CONCLUSIONS

This study demonstrates that incorporating waste tire rubber into polyester-based composites significantly improves their machinability. The presence of rubber particles within the matrix resulted in a substantial reduction in the specific cutting coefficient compared to composites reinforced exclusively with fiberglass. This enhancement is attributed to the rubber's inherent ability to absorb and dissipate energy during the cutting process, effectively mitigating the formation of large chip loads and reducing cutting forces.

Furthermore, the study confirms the inverse relationship between feed rate and specific cutting resistance, a trend observed in conventional machining processes. This reduction is likely due to the formation of larger shear zones, enhanced heat dissipation, and altered chip morphology at higher feed rates. However, it is crucial to note that excessive feed rates can adversely impact tool life and compromise the quality of the machined surface.

These findings provide valuable insights for optimizing machining operations involving hybrid polyester composites, However, limitations exist, such as a limited scope of material variations and cutting conditions, the use of hand lay-up for composite fabrication, and reliance on drilling force as the primary performance indicator.

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