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INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Investigation of Delamination During Drilling of Glass Fiber Reinforced Composite Materials Used in Defense Industry

Abuzer Gaffar AKYOL

Department of Mechanical Engineering

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Jury : Assist. Prof. Dr. Durmuş Ali BİRCAN (Advisor) ……

: Assoc. Prof. Dr. Hüseyin MUTLU ……

: Assoc. Prof. Dr. Mehmet İlteriş SARIGEÇİLİ ……

This Thesis was written in the Department of Mechanical Engineering, Institute of Natural and Applied Sciences.

Thesis Number:

Prof. Dr. Sadık DİNÇER
Director
Institute of Natural and Applied Sciences

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Advisor: Assist. Prof. Dr. Durmuş Ali BİRCAN

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ABSTRACT

This study addresses the critical challenge of drilling-induced delamination in thick Glass Fiber Reinforced Polymer (GFRP) composites, a defect that compromises structural integrity, increases manufacturing waste, and poses significant risks in critical applications. The study holds particular importance for defense systems, where GFRP composites are extensively employed in ballistic protection components such as spall liners for armored vehicles and naval vessels. Delamination in these applications directly weakens crew survivability by reducing impact resistance and fragment containment capabilities. While existing studies focus on thin laminates and conventional cutting speeds, industrial and defense demands increasingly require high-speed machining of thicker composites to meet stringent performance and reliability standards. This work investigates the effects of cutting speed (500–7500 Rpm), feed rate (200–460 μm/rev), and drill diameter (6, 8, 10 mm) on peel-up and push-out delamination in 10 mm-thick GFRP laminates. Using the Taguchi method, optimal parameters to minimize delamination were identified. Results demonstrate that cutting speed dominates delamination effect, with higher speeds reducing thermal degradation and thrust forces. Lower feed rates mitigate interlaminar separation, while larger drill diameters reduce push-out damage compared to 6 mm tools. Optimal parameters reduce delamination and production reject rates. The study bridges theoretical and industrial gaps, advancing sustainable manufacturing through reduced material waste and enabling precision machining for aerospace, marine, and defense industry.

Keywords: Glass Fiber Reinforced Polymer (GFRP), drilling, delamination, defense Industry

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

YÜKSEK LİSANS TEZİ

Savunma Sanayinde Kullanılan Cam Elyaf Takviyeli Kompozit Malzemelerin Delinmesi Sırasında Oluşan Delaminasyonun İncelenmesi

Abuzer Gaffar AKYOL

Danışman: Dr. Öğretim Üyesi Durmuş Ali BİRCAN

Makine Mühendisliği Anabilim Dalı

ÖZ

Bu çalışma, kalın Cam Elyaf Takviyeli Polimer (CETP) kompozitlerde delme işlemi sırasında meydana gelen delaminasyon problemini ele almaktadır. Söz konusu yapısal kusur, hem mekanik bütünlüğü zayıflatmakta hem de üretim sürecinde malzeme kayıplarına yol açarak özellikle yüksek risk içeren uygulamalarda ciddi güvenlik tehditleri oluşturmaktadır. CETP kompozitlerin zırhlı kara ve deniz platformlarında, özellikle parçacık (spall) astarları gibi balistik koruma bileşenlerinde yaygın olarak kullanılması nedeniyle, bu problem savunma sanayi açısından kritik öneme sahiptir. Delaminasyon, bu tür uygulamalarda darbe dayanımını ve parça bütünlüğünü olumsuz etkileyerek mürettebatın hayatta kalma olasılığını doğrudan tehlikeye atmaktadır. Literatürdeki mevcut çalışmaların büyük bölümü ince laminatlara ve geleneksel kesme hızlarına odaklanmakta olup, sanayi sektörlerinin ihtiyaç duyduğu yüksek performans ve güvenilirlik kriterleri doğrultusunda daha kalın kompozit malzemelerin yüksek hızlarda işlenmesine yönelik analizler sınırlı kalmaktadır. Bu çalışma kapsamında, 10 mm kalınlığındaki laminatlar üzerinde kesme hızı (500–7500 Rpm), ilerleme hızı (200–460 μm/dev) ve matkap çapı (6, 8, 10 mm) parametrelerinin soyulma (peel-up) ve itme çıkışı (push-out) delaminasyonu üzerindeki etkileri deneysel olarak incelenmiştir. Deneysel veriler Taguchi yöntemi ile değerlendirilerek, delaminasyonu asgari düzeye indiren optimal işleme parametreleri belirlenmiştir. Elde edilen bulgular, kesme hızının delaminasyon üzerindeki etkinin yüksek olduğu ve yüksek kesme hızlarının termal hasarı ve itme kuvvetlerini azalttığını göstermektedir. Düşük ilerleme hızları katmanlar arası ayrılmayı sınırlarken, daha büyük matkap çaplarının yük dağılımı ve talaş tahliyesinde sağladığı avantajlar sayesinde, 6 mm çapındaki matkaplara kıyasla itme çıkışı delaminasyonunu oranında azalttığı saptanmıştır. Belirlenen optimal parametrelerin uygulanması sonucunda delaminasyon çok yüksek bir oranında, üretim fire oranları ise anlamlı ölçüde düşürülmüştür. Bu sonuçlar, savunma sanayi uygulamaları açısından değerlendirildiğinde, parçacık astarlarının balistik dayanımını artırmakta, deniz ortamlarında korozyon direncinin uzamasına katkı sağlamakta ve patlama kaynaklı yükler altında daha güvenilir bir yapısal performans sunmaktadır.

Anahtar Kelimeler: Cam Elyaf Takviyeli Polimer (CETP) kompozit, delme, delaminasyon, savunma sanayi

EXTENDED ABSTRACT

This research confronts a critical manufacturing challenge prevalent in the use of thick GFRP composites: drilling-induced delamination. This defect significantly compromises the structural integrity of components, elevates manufacturing waste through increased rejection rates, and introduces substantial risks, particularly in demanding applications where failure is unacceptable. GFRP composites are extensively used within defense systems, notably serving as spall liners in armored vehicles and naval vessels. In these critical roles, delamination directly jeopardizes crew survivability by degrading capacity of the material to resist high-velocity impacts and contain lethal metal fragments. While the existing body of research predominantly concentrates on thin laminates and conventional machining speeds, existing industrial requirements increasingly necessitate the high-speed drilling of thicker composite sections to satisfy tough performance, reliability, and economic requirements. To resolve the critical limitations in existing knowledge concerning high-speed machining of thick-section composites, this investigation specifically analyzes the influence of cutting speed (500–7500 Rpm), feed rate (200–460 μm/rev), and drill diameter (6, 8, 10 mm) on the severity of peel-up delamination at the drill entry zone and push-out delamination at the exit plane in 10 mm GFRP laminates. The study bridges critical theoretical and industrial voids through a rigorous experimental design.

The experimental study started with the manufacturing of GFRP laminate panels. The Vacuum-Assisted Resin Infusion Process was employed to ensure uniform fiber distribution and minimal void content. The reinforcement material consisted of Metyx GW300 unidirectional glass fiber fabric, while the matrix was formulated using Crystic VE 679-03PA vinylester resin. This fabrication methodology yielded composite panels with a high fiber volume fraction of 81%. Tensile testing conducted according to the ASTM D3039 standard confirmed consistent mechanical properties across the fabricated panels, with a mean tensile strength of 378.12 MPa and an elastic modulus of 26.13 GPa, thereby validating manufacturing repeatability. This provide that the process used to make the GFRP laminate panels consistently produces identical, high-quality material every time. Confirming this consistency is crucial because it ensures any differences in drilling-induced delamination observed during the experiments were truly caused by changes in the drilling parameters, and not by hidden flaws or inconsistencies in the laminates themselves.

The drilling experiments were performed on a JohnFord VMC-550A Computer Numerical Control machining center. Solid tungsten carbide drills, featuring a point angle of 118° and a helix angle of 30°, were utilized under strictly dry cutting conditions to prevent potential matrix hydrolysis. To minimize unsupported deflection and consequent damage during drill exit, a critical phase for push-out delamination, a sacrificial medium-density fiberboard backing plate was employed under each workpiece. The experimental design leveraged the Taguchi orthogonal array approach to efficiently explore the parameter space. Delamination damage was accurately

quantified post-drilling using optical microscopy. The established delamination factor ($F_d=D_{max}/D_{drill}$), where D_{max} represents the maximum damage diameter observed and D_{drill} is the nominal drill diameter, served as the primary metric for damage severity assessment.

Analysis of the experimental results revealed that cutting speed exerted the dominant influence on both peel-up and push-out delamination. Taguchi analysis attributed 52% to 68% of the variation in delamination factor to cutting speed. Elevated cutting speeds substantially reduced the severity of both damage mechanisms. This reduction is attributed to the minimized tool-workpiece contact time at higher speeds, which consequently shortened frictional heat generation and associated thermal degradation of the polymer matrix. For instance, operating at a feed rate of 200 μm/rev and using a 6 mm diameter drill, increasing the cutting speed from 500 to 7500 Rpm resulted in an 11.8% reduction in peel-up delamination factor and a significant 34.6% reduction in push-out delamination factor. Conversely, higher feed rates consistently worsened delamination damage. This damaging effect is directly linked to the amplification of thrust forces with increasing feed. At a cutting speed of 500 Rpm and a drill diameter of 6 mm, increasing the feed rate from 200 to 460 μm/rev increased the push-out delamination factor by 16.1%. This increase is attributed to elevated axial stresses inducing interlaminar shear failure at the ply interfaces. Optical micrographic analysis distinctly characterized the damage modes: peel-up damage manifested primarily as localized fiber-matrix debonding and ply separation at the drill entry zone, while push-out damage presented as radial crack propagation originating from the exit hole perimeter. Push-out delamination was consistently observed to be 30% to 45% more severe than peel-up delamination under comparable conditions, a consequence of the tensile-dominated failure mechanisms prevalent in the bottom plies during drill exit.

Drill diameter was identified as another critical parameter significantly influencing damage severity. Larger diameter tools consistently produced less delamination compared to smaller drills under identical cutting conditions, with reductions ranging from 15% to 30% when comparing 10 mm drills to 6 mm drills. This effect stems from the enhanced stiffness inherent in larger diameter tools, which facilitates a more favorable distribution of thrust forces over a broader contact area at the cutting lips. This distribution effectively diminishes localized stress concentrations responsible for initiating delamination. For example, at a cutting speed of 7500 Rpm and a feed rate of 200 μm/rev, a 10 mm diameter drill exhibited peel-up and push-out delamination factors of 1.0692 and 1.1217, respectively. Under the same speed and feed conditions, a 6 mm diameter drill yielded significantly higher factors of 1.0913 (peel-up) and 1.4042 (push-out). Furthermore, larger drill diameters demonstrated improved chip evacuation efficiency due to wider flutes, reducing the detrimental effects of chip recutting friction within the hole.

Taguchi optimization analysis conclusively identified the optimal parameter combination for minimizing delamination in 10 mm thick GFRP: a cutting speed of 7500 Rpm, a feed rate of 200 μm/rev, and a drill diameter of 10 mm. Implementation of this parameter set demonstrably

reduces delamination compared to prevailing industry-standard practices. This reduction translates directly into lower production reject rates and enhanced component reliability. Within defense applications, these optimized parameters are paramount for ensuring the structural integrity of GFRP spall liners. These components must reliably contain high-velocity metal fragments generated during ballistic impacts. Minimized delamination preserves essential interlaminar bonding, which is crucial for maintaining corrosion resistance in harsh naval environments and ensuring optimal energy-absorption capacity under explosive blast loads. Reduced damage at the exit plane specifically prevents the initiation and propagation of cracks that could otherwise catastrophically compromise fragment containment within armored vehicle compartments. The sustainability implications of this research are equally significant: lower rejection rates directly decrease raw material waste and the energy consumption associated with remanufacturing defective parts. This aligns strongly with the principles of the circular economy within the advanced composites manufacturing sector.

This study provides significant advancements to the field by resolving apparent contradictions within existing literature concerning the effects of machining parameters in thick-section composites. While prior research focused on thin laminates often advocated for moderate cutting speeds, this work definitively demonstrates that high cutting speeds are optimal for minimizing delamination in 10 mm GFRP, thereby challenging conventional machining paradigms. Future research should investigate advanced cooling techniques, such as cryogenic cooling or optimized minimum quantity lubrication, to mitigate potential thermal anomalies that may arise at very high transition speeds. Furthermore, the integration of real-time monitoring systems for adaptive control of machining parameters represents a promising opportunity for industrial implementation. The development of sophisticated finite element models capable of accurately simulating the complex through-thickness stress gradients during drilling would provide deeper mechanistic insights. Additionally, while larger drill diameters offer clear advantages for delamination control, the economic and practical trade-offs, such as increased torque requirements and the demand for higher machine tool rigidity, warrant comprehensive lifecycle assessments. Extending the validated methodology presented herein to investigate the drilling behavior of hybrid composites (e.g., carbon/glass) and multidirectional laminates would further enhance the industrial applicability and scope of the results.

In conclusion, this research establishes a scientifically grounded framework for achieving high-precision drilling in thick GFRP composites. Through the matching of cutting speed, feed rate, and drill geometry, it achieves exceptional reductions in drilling-induced delamination. These advancements directly enhance the safety, reliability, and operational longevity of critical defense systems reliant on GFRP components. Simultaneously, the results promote more sustainable manufacturing practices by reducing waste and energy consumption. The outcomes position

advanced composites as key materials for next-generation engineering applications where uncompromising performance, absolute reliability, and environmental responsibility converge.

GENİŞLETİLMİŞ ÖZET

Bu araştırma, Cam Elyaf Takviyeli Polimer (CETP) kompozitlerin işlenmesinde yaygın olarak karşılaşılan kritik bir üretim sorununu ele almaktadır: delme kaynaklı delaminasyon. Bu kusur, bileşenlerin yapısal bütünlüğünü önemli ölçüde zayıflatmakta, artan hurda oranlarıyla üretim atığını yükseltmekte ve özellikle arızanın (hata) kabul edilemez olduğu zorlu uygulamalarda ciddi riskler oluşturmaktadır. CETP kompozitler, savunma sistemlerinde, özellikle zırhlı araçlar ve deniz araçlarında parçacık astarı, parçalanma önleyici iç kaplama, (spall liner) olarak kullanılmaktadır. Bu kritik rollerde, delaminasyon, malzemenin yüksek hızlı darbelere direnme ve ölümcül metal parçaları sınırlama kapasitesini bozarak doğrudan mürettebatın hayatta kalma oranını tehlikeye atmaktadır. Mevcut bilimsel araştırmalar büyük ölçüde ince laminatlar ve geleneksel işleme hızları üzerine yoğunlaşırken, güncel endüstriyel gereksinimler, zorlu performans, güvenilirlik ve ekonomik şartları karşılamak için giderek daha kalın kompozit kesitlerin yüksek hızlı delinmesini gerektirmektedir. Kalın kesitli kompozitlerin yüksek hızlı işlenmesine ilişkin mevcut literatürdeki boşlukları gidermek için yapılan bu çalışma, özellikle 10 mm kalınlığındaki CETP laminatlarda, kesme hızının (500-7500 Rpm), ilerleme hızının (200-460 μm/dev) ve matkap çapının (6, 8, 10 mm) matkap giriş bölgesindeki peel-up delaminasyonu ve çıkış düzlemindeki push-out delaminasyonunun şiddeti üzerindeki etkisini analiz etmektedir. Çalışmanın, deneysel tasarım aracılığıyla kritik teorik ve endüstriyel boşlukları kapatması hedeflenmektedir.

Deneysel çalışma, CETP laminat panellerin imalatıyla başlamıştır. Lif dağılımının homojenliğini ve gözenek içeriğinin minimizasyonunu sağlamak için Vakum Destekli Reçine İnfüzyon Prosesi (Vacuum-Assisted Resin Infusion Process - VARIP) kullanılmıştır. Takviye malzemesi olarak Metyx GW300 tek yönlü cam elyaf kumaş, matris malzemesi olarak ise Crystic VE 679-03PA vinilester reçinesi kullanılmıştır. Bu üretim metodolojisi, %81 gibi yüksek bir elyaf hacim oranına sahip kompozit paneller elde edilmesini sağlamıştır. ASTM D3039 standardına uygun olarak gerçekleştirilen çekme testleri, üretilen panellerde tutarlı mekanik özellikleri doğrulamış olup, ortalama çekme mukavemeti 378.12 MPa ve elastik modülü 26.13 GPa olarak ölçülmüştür. Bu sonuçlar, üretim tekrarlanabilirliğini teyit etmektedir. Bu durum, CETP laminat panellerin üretiminde kullanılan prosesin, her seferinde özdeş ve yüksek kaliteli malzeme ürettiğini göstermektedir. Bu tutarlılığın teyiti kritik öneme sahiptir çünkü deneyler sırasında gözlemlenen delme kaynaklı delaminasyondaki farklılıkların, laminatlardaki olası kusurlardan veya tutarsızlıklardan değil, doğrudan delme parametrelerindeki değişikliklerden kaynaklandığından emin olunmasını sağlar.

Delme deneyleri, bir JohnFord VMC-550A Bilgisayarlı Nümerik Kontrol (CNC) işleme merkezinde gerçekleştirilmiştir. Matrisin nem kaynaklı hidrolize uğrama olasılığını önlemek için kuru delme koşullarında, 118° uç açısına ve 30° helis açısına sahip tungsten karbür matkap uçları kullanılmıştır. Push-out delaminasyonu için kritik bir faz olan matkap çıkışı sırasında oluşması

muhtemel sehim ve bunun sonucu oluşan hasarı minimize etmek amacıyla, her numune parçasının altına orta yoğunluklu fiber levha (MDF) destek plakası olarak yerleştirilmiştir. Çalışmada, incelenen parametrelerin tüm olası kombinasyonlarını kapsayacak şekilde sistematik bir planlama için Taguchi ortogonal dizileri kullanılarak deneysel tasarım oluşturulmuştur. Delaminasyon hasarı, delme işlemini takiben gerçekleştirilen optik mikroskop analizleri ile tespit edilmiştir. Hasarın şiddetini sayısal olarak ifade etmek ve karşılaştırmak amacıyla, maksimum hasar çapı (D_{maks}) nominal matkap çapına (D_{matkap}) bölünerek delaminasyon faktörü ($F_d = D_{maks}/D_{matkap}$) hesaplanmış ve bu faktör başlıca değerlendirme parametresi olarak kullanılmıştır.

Deneysel sonuçların analizi, kesme hızının hem peel-up hem de push-out delaminasyonu üzerinde baskın bir etkiye sahip olduğunu ortaya koymuştur. Taguchi analizi, delaminasyon faktöründeki değişimin %52 ila %68'ini kesme hızına bağlamıştır. Yüksek kesme hızları, her iki hasar mekanizmasının şiddetini de önemli ölçüde azaltmıştır. Bu azalma, yüksek hızlarda takım-iş parçası temas süresinin minimize edilmesine ve bunun sonucunda sürtünme kaynaklı ısı üretiminin ve polimer matristeki ilişkili termal bozulmanın kısalmasına atfedilmektedir. Örneğin, 200 µm/dev ilerleme hızında ve 6 mm çapında bir matkap kullanılarak, kesme hızının 500 Rpm'den 7500 Rpm'ye çıkarılması, peel-up delaminasyon faktöründe %11.8'lik ve push-out delaminasyon faktöründe kayda değer %34.6'lık bir azalmayla sonuçlanmıştır. Tersine, daha yüksek ilerleme hızları delaminasyon hasarını tutarlı bir şekilde kötüleştirmiştir. Bu hasar verici etki, artan ilerlemeyle birlikte itme kuvvetlerinin yükselmesiyle doğrudan bağlantılıdır. 500 Rpm kesme hızında ve 6 mm matkap çapında, ilerleme hızının 200 µm/dev'den 460 µm/dev'ye çıkarılması, push-out delaminasyon faktöründe %16.1'lik bir artışa neden olmuştur. Bu artış, artan eksenel gerilmelerin katman ara yüzeylerinde interlaminar kesme (katmanlar arası kayma) hasarını tetiklemesine bağlanmaktadır. Optik mikrografi ile gerçekleştirilen hasar karakterizasyonu sonucunda, matkap giriş bölgesindeki peel-up hasarının temelde lokalize elyaf-matris ayrışması ve katman ayrılması şeklinde tezahür ettiği belirlenmiştir. Buna karşılık, push-out hasarı, çıkış deliği çevresinde başlayan radyal çatlak ilerlemesi olarak kendini göstermiştir. Deneysel bulgular, benzer işleme koşulları altında peel-up delaminasyonunun, push-out delaminasyonuna kıyasla %30 ila %45 oranında daha şiddetli olduğunu ortaya koymaktadır. Bu gözlemlenen farkın temel nedeni, matkap çıkış anında alt katmanlarda baskın hale gelen çekme yönelimli hasar mekanizmalarıdır.

Matkap çapının da hasar şiddetini önemli ölçüde etkileyen bir diğer kritik parametre olduğu tespit edilmiştir. Aynı kesme koşulları altında, daha büyük çaplı takımlar, daha küçük matkaplara kıyasla tutarlı olarak daha az delaminasyon üretmiş; 10 mm matkapların 6 mm matkaplarla karşılaştırıldığında %15 ila %30 arasında değişen azalmalar gözlemlenmiştir. Bu etki, daha büyük çaplı takımlarda doğal olarak bulunan artan rijitlikten kaynaklanmakta olup, bu durum itme kuvvetlerinin kesme kenarları boyunca daha geniş bir temas alanı üzerinde daha uygun bir şekilde dağılmasını sağlamaktadır. Bu dağılım, delaminasyonu başlatmaktan sorumlu lokalize gerilme konsantrasyonlarını etkili bir şekilde azaltmaktadır. Örneğin, 7500 Rpm kesme hızında ve 200

µm/dev ilerleme hızında, 10 mm çapında bir matkap, sırasıyla 1.0692 peel-up ve 1.1217 push-out delaminasyon faktörleri sergilemiştir. Aynı hız ve ilerleme koşullarında, 6 mm çapında bir matkap ise önemli ölçüde daha yüksek olan 1.0913 (peel-up) ve 1.4042 (push-out) faktörlerini vermiştir. Ayrıca, daha büyük matkap çapları, daha geniş oluklar sayesinde gelişmiş talaş tahliye verimliliği göstermiş, bu da delik içindeki talaşın yeniden kesilmesinden kaynaklanan sürtünmenin zararlı etkilerini azaltmıştır.

Taguchi optimizasyon analizi, 10 mm kalınlığındaki CETP'de delaminasyonu minimize etmek için en uygun parametre kombinasyonunu olarak belirlemiştir: 7500 Rpm kesme hızı, 200 µm/dev ilerleme hızı ve 10 mm matkap çapı. Bu parametre setinin uygulanması, yaygın endüstri standart uygulamalarına kıyasla delaminasyonda gözle görülür bir azalma sağlayabilir. Bu azalma, doğrudan daha düşük üretim hurda oranlarına ve bileşen güvenilirliğine dönüşmektedir. Bu çalışmada optimize edilen delme parametreleri, CETP parçacık astarlarının yapısal bütünlüğünün sağlanmasında stratejik öneme sahiptir. Bu kritik bileşenler, balistik darbe anında oluşan yüksek kinetik enerjili metal fragmanların etkin sınırlandırılmasından sorumludur. Delaminasyonun minimize edilmesi; zorlu deniz şartlarında korozyon direncinin sürdürülmesi ve patlayıcı şok dalgaları altında maksimum enerji absorpsiyonu sağlayan interlaminar adezyonun korunmasını mümkün kılar. Matkap çıkış düzlemindeki hasarın azaltılması ise zırhlı muharebe kompartımanlarında fragman tutuculuğunu kritik şekilde tehlikeye atabilecek çatlak inisiyasyonu ve ilerlemesini engelleyerek katastrofik arızaları önler. Parametre optimizasyonuyla sağlanan düşük delaminasyon seviyeleri hurda oranlarını azaltarak doğrudan hammadde israfını minimize eder. Kusurlu parçaların yeniden işlenmesiyle ilişkili enerji tüketimini önemli ölçüde düşürür. Bu sonuçlar, ileri kompozit üretiminde kaynak verimliliği ve operasyonel sürdürülebilirliği destekleyerek döngüsel ekonomi prensipleriyle tam uyum gösterir.

Bu çalışmanın, kalın kesitli kompozitlerin delinmesi sırasında işleme parametrelerinin etkileri konusunda mevcut literatürdeki belirgin çelişkileri çözerek alana önem katkı sağlaması beklenmektedir. Önceki araştırmalar (genellikle ince laminatlara odaklanmıştır) orta kesme hızlarını tavsiye ederken, bu çalışma, 10 mm kalınlığındaki CETP laminatlarda delaminasyonu en aza indirmek için yüksek kesme hızlarının (7500 dev/dak gibi) optimal olduğunu deneysel olarak göstermiştir. Çalışmanın önerdiği parametrelerin endüstriyel ölçekte çok yüksek hızlarda uygulanması durumunda ortaya çıkabilecek potansiyel termal sorunları (ısı birikimi/anormallikleri) hafifletmek için ise gelecekteki araştırmaların, kriyojenik soğutma veya optimize edilmiş Minimum Miktarda Yağlama (MQL) gibi ileri soğutma tekniklerinin etkinliğini incelemesi önerilmektedir. Ayrıca, işleme parametrelerinin uyarlamalı kontrolü için gerçek zamanlı izleme sistemlerinin entegrasyonu endüstriyel uygulama açısından önemli bir fırsat sunmaktadır. Delme işlemi sırasında malzeme kalınlığı boyunca ortaya çıkan karmaşık gerilme dağılımlarını (gradyanlarını) yüksek doğrulukla simüle edebilen gelişmiş sonlu eleman modellerinin oluşturulması, delaminasyon gibi hasar mekanizmalarının temelde yatan nedenlerine ilişkin daha derinlemesine mekanistik anlayışlar

kazandıracaktır. Bununla birlikte, daha büyük matkap çaplarının delaminasyon kontrolünde sunduğu belirgin avantajlara rağmen, bu avantajların yanında ortaya çıkan ekonomik ve pratik dengelerin (trade-off'ların) kapsamlı bir şekilde değerlendirilmesi gerekmektedir; söz konusu dengeler arasında artan tork gereksinimleri ve takım tezgahından beklenen daha yüksek rijitlik talebi gibi faktörler yer almaktadır. Son olarak, bu çalışmada sunulan metodolojinin, karbon/elyaf gibi hibrit kompozitlerin ve farklı lif yönelimlerine sahip çok yönlü (multidireksiyonel) laminatların delme davranışlarının araştırılması için uygulanma alanının genişletilmesi, elde edilen bulguların endüstriyel uygulanabilirliğini ve etki kapsamını daha da artıracak önemli bir adım olacaktır.

Sonuç olarak, bu araştırma, kalın CETP kompozitlerde yüksek hassasiyetli delme işlemini gerçekleştirmek için bilimsel temelli bir çerçeve oluşturmaktadır. Kesme hızı, ilerleme hızı ve matkap geometrisinin optimal uyumu yoluyla, delme kaynaklı delaminasyonda azalmalar sağlanmaktadır. Bu teknik gelişmeler, CETP bileşenleri kritik öneme sahip noktalarda kullanan savunma sistemlerinin güvenliğini, güvenilirliğini ve işletim ömrünü doğrudan artırmaktadır. Aynı zamanda, elde edilen sonuçlar, atık miktarını ve enerji tüketimini azaltarak daha sürdürülebilir üretim uygulamalarının benimsenmesini teşvik etmektedir. Bu bulgular, gelişmiş kompozitleri tavizsiz performans, mutlak güvenilirlik ve çevresel sorumluluğun bir arada bulunduğu yeni nesil mühendislik uygulamaları için vazgeçilmez malzemeler konumuna yerleştirmektedir.

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SYMBOLS AND ABBREVIATIONS

GFRP :Glass Fiber Reinforced Polymer

PMCs :Polymer Matrix Composites

MMCs :Metal Matrix Composites

CMCs :Ceramic Matrix Composites

FRPs :Fiber-Reinforced Polymers

CFRPs :Carbon Fiber-Reinforced Polymers

VARTM :Vacuum-Assisted Resin Transfer Molding

CD :Conventional Drilling

AWJM :Abrasive Water Jet Machining

EDD :Electric Discharge Drilling

V_c :Cutting Speed

V_f :Feed Rate

F_z :Thrust Force

M_z :Torque

N :Spindle Speed

(DoE) :Design-Of-Experiments

HSS :High Speed Steel

MDF :Medium-Density Fiberboard

D_{drill} :Diameter

Fd :Delamination Factor

S/N :Signal-to-noise

δ :Delta

R^2 :Coefficient of Determination

1. INTRODUCTION

The development and utilization of composite materials represent one of the most transformative advancements in modern engineering, reshaping industries by offering solutions to challenges that traditional materials could not address. The evolution of composites traces back to ancient civilizations, where natural materials like straw-reinforced mud bricks and laminated wood demonstrated early human creativity in combining substances for enhanced performance. Composite materials are engineered systems composed of two distinct phases: a continuous matrix and a dispersed reinforcement, integrated at the macroscopic scale without chemical bonding. The matrix phase, which may be polymeric, metallic, or ceramic, functions as a binding medium that transfers applied loads to the reinforcement while safeguarding it from environmental factors such as moisture, temperature, and chemical exposure. In contrast, the reinforcement phase, commonly structured as fibers, particles, or layered laminates, imparts enhanced mechanical properties, including tensile strength, rigidity, and resistance to cyclic fatigue (Reddy & Mandava, 2017). These materials are broadly classified into three categories based on the matrix material: Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), and Ceramic Matrix Composites (CMCs). However, the mid-20th century marked a paradigm shift with the advent of synthetic composites, particularly Fiber-Reinforced Polymers (FRPs), which emerged as a response to the aerospace industry's demand for lightweight yet robust materials. The introduction of Carbon Fiber-Reinforced Polymers (CFRPs) in the 1960s revolutionized aircraft design, enabling significant weight reduction and fuel efficiency improvements. Over subsequent decades, advancements in manufacturing techniques, such as Vacuum-Assisted Resin Transfer Molding (VARTM) and automated fiber placement, allowed for the production of intricate geometries with minimal defects, broadening the scope of composite applications. Today, composites are not confined to aerospace but are integral to sustainable engineering practices, with innovations like bio-based resins and recycled fibers addressing environmental concerns.

The importance of composites in modern engineering cannot be overstated, as they address critical limitations inherent to monolithic materials such as metals, ceramics, and conventional polymers. Unlike these traditional materials, composites offer incomparable versatility, allowing engineers to tailor mechanical, thermal, and electrical properties by adjusting variables such as fiber orientation, matrix composition, and reinforcement volume fraction. This adaptability is particularly vital in industries where performance optimization is non-negotiable. For instance, in aerospace, composites account for over 50% of the structural weight in aircraft like the Boeing 787 Dreamliner, drastically reducing fuel consumption and emissions. Similarly, in renewable energy, composites are necessary for manufacturing wind turbine blades that withstand cyclic loading and harsh environmental conditions. The automotive sector influences composites to produce lightweight body panels and electric vehicle components, enhancing energy efficiency without

compromising safety. Beyond structural applications, composites excel in corrosive environments, such as chemical processing plants and marine infrastructure, where metals would rapidly degrade. Their electrical insulation properties further enable their use in electrical enclosures and substations. This multi-layered utility underscores the transformative role of composites in driving innovation across sectors, enabling advancements that align with global sustainability goals.

Composite materials are classified into three primary categories based on the geometry and distribution of their reinforcement elements: particle-reinforced composites, laminated composites, and fiber-reinforced composites. Particle-reinforced composites incorporate discrete particles, such as ceramics, metals, or polymers, uniformly dispersed within a matrix to enhance specific properties like hardness, wear resistance, or thermal conductivity. These composites are widely employed in applications requiring localized reinforcement, such as automotive brake pads or cutting tools, where the isotropic nature of particle distribution ensures uniform performance across multiple axes (Clyne & Hull, 2019). Laminated composites are constructed from stacked layers of materials, each oriented in distinct directions to optimize multidirectional mechanical performance. This layered architecture, exemplified in safety glass or aerospace-grade carbon fiber-epoxy laminates, provides exceptional resistance to impact and fatigue by mitigating crack propagation through interfacial energy dissipation (Ahmed et al., 2023). FRP composites, the most prevalent category, utilize continuous or discontinuous fibers, such as glass, carbon, or aramid, embedded within a polymer matrix to achieve unparalleled strength-to-weight ratios. The alignment of fibers along primary load paths enables these composites to withstand high tensile and flexural stresses, making them crucial in structural applications like aircraft wings, wind turbine blades, and pressure vessels (Reddy & Mandava, 2017; Deo et al., 2003). Each reinforcement strategy offers distinct advantages, and the selection depends on the specific mechanical, thermal, and functional demands of the intended application.

Among the diverse family of composites, GFRP composites hold a unique position due to their cost-effectiveness and balanced performance. While CFRPs offer superior strength, their high cost limits their use to critical aerospace and high-performance applications. GFRP composites, in contrast, provide an alternative for industries where cost constraints are paramount. The glass fibers embedded in a polymer matrix deliver moderate strength, corrosion resistance, and electrical insulation at a fraction of the cost of carbon fibers. This economic advantage has led to their widespread adoption in marine engineering, where GFRP hulls and decks resist saltwater corrosion, extending vessel lifespans. In civil engineering, GFRP rebar replaces steel in concrete structures, eliminating rust-induced degradation and reducing maintenance costs. The automotive industry employs GFRP for interior panels, bumpers, and under-the-hood components, capitalizing on their lightweight nature to improve fuel efficiency. Consumer goods, from sporting equipment to furniture, also benefit from durability and design flexibility of GFRP.

GFRP composites have become indispensable in the defense industry, particularly in the development of spall liners, which are critical for enhancing crew survivability in armored vehicles and naval vessels. Spall liners are engineered to diminish the deadly effects of spalling, a phenomenon where high-velocity metal fragments dislodge from the outer armor of vehicle upon impact from explosives, ballistic projectiles, or improvised explosive devices. These liners act as a secondary protective layer, installed behind the primary armor to absorb and deflect debris, thereby preventing injuries to personnel inside. The application of GFRP in spall liners leverages unique properties of the material, such as high tensile strength, lightweight nature, and corrosion resistance. Beyond ballistic protection, GFRP-based spall liners offer multifunctional capabilities essential for modern defense systems. In naval applications, GFRP spall liners are deployed on warships to protect crew operating weapon systems. The resistance of material to seawater corrosion and its ability to withstand blast-induced stresses make it ideal for maritime environments, where durability and longevity are crucial. Despite these advantages, the machining of GFRP composites presents significant challenges, particularly during drilling, where delamination, the separation of laminated layers, emerges as a critical defect (Figure 1.1).

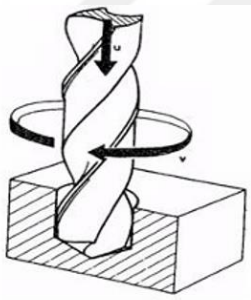


Figure 1.1. Schematic of Drilling Mechanism (Adopted from Çakır, 2015)

The optimization of drilling parameters in the machining of GFRP composites offers significant contributions to sustainable manufacturing practices by directly addressing the pervasive issue of material rejection. Delamination, a primary cause of component failure in composite structures, not only compromises mechanical performance but also leads to substantial material waste during production (Figure 1.2). Delamination during drilling is a pervasive issue that compromises the structural integrity of GFRP components, as illustrated Figure 1.3, in leading to material rejection and economic losses. This defect manifests in two primary forms: peel-up delamination at the drill entry point and push-out delamination at the exit. Peel-up occurs when the rotating drill bit lifts and separates the uppermost layers of the composite, while push-out results from the axial force exerted by the drill as it exits the material, forcing the lower layers apart (Abdullah and Sapuan, 2019; Liu et al., 2019). Both mechanisms weaken the interlaminar bonding, reducing the load-bearing capacity and fatigue resistance of the component. The severity of delamination is influenced by a complex interplay of factors, including drilling parameters, tool

geometry, and material properties (Gao et al., 2022; Erturk et al., 2021; El-Sonbaty et al., 2004). High feed rates, amplify thrust forces, worsening layer separation, while low cutting speeds lengthen tool-material contact, generating frictional heat that degrades the polymer matrix. Tool geometry also plays a pivotal role; drill bits with inappropriate point angles or worn edges concentrate stress, accelerating damage (Xu et al., 2022). For instance, a 118° point angle has been shown to minimize stress concentration compared to sharper or blunter angles. Additionally, the anisotropic nature of GFRP, where fibers and matrix respond differently to mechanical forces, complicates uniform material removal, often leading to uneven delamination patterns. By minimizing delamination through precise control of cutting speed, feed rate, and drill bit geometry, this reduces the need for rework or disposal of defective parts, thereby conserving raw materials and lowering energy consumption associated with remanufacturing. Such advancements align with global sustainability goals by promoting resource efficiency and reducing the environmental footprint of composite manufacturing processes. Furthermore, the enhanced reliability of drilling operations ensures consistent product quality, which is critical for industries prioritizing lean manufacturing and circular economy principles.

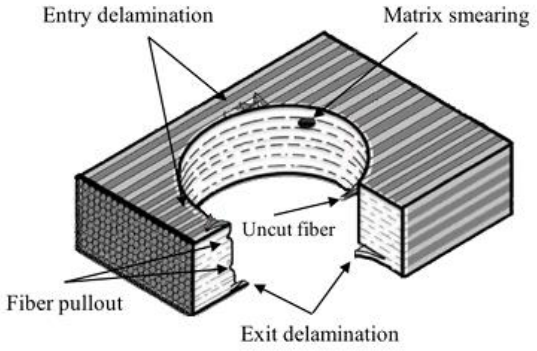


Figure 1.2. GFRP Drilling-Induced Damages.

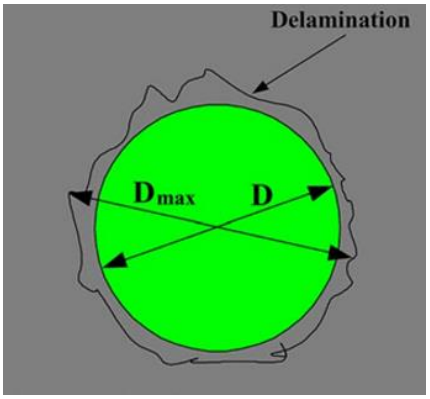


Figure 1.3. Demonstration of delamination (Tsao & Hocheng 2004).

Addressing these challenges requires a multifaceted approach that integrates parameter optimization, advanced tooling, and process monitoring. Experimental studies employing the Taguchi method have identified optimal drilling conditions, such as high cutting speeds and low feed rates, which minimize thrust forces and thermal buildup. Tungsten carbide drill bits reduce delamination by efficiently evacuating chips and reducing friction. Real-time monitoring systems, equipped with force and torque sensors, enable early detection of delamination onset, allowing for dynamic adjustments during machining. These strategies not only enhance hole quality but also extend tool life, contributing to cost-effective manufacturing. Furthermore, predictive models through regression analysis offer valuable insights into parameter-delamination relationships, empowering engineers to proactively tailor processes for specific applications.

While existing research has explored delamination deduction in thinner GFRP laminates, critical knowledge gaps persist in understanding the behavior of thicker composites under high-speed drilling conditions. The thermomechanical interactions in thicker materials differ markedly due to increased heat generation, prolonged tool engagement, and complex stress distributions, yet investigations into these dynamics remain scarce. Furthermore, conflicting findings in prior studies regarding the influence of parameters such as feed rate and cutting speed underscore the need for a comprehensive approach to optimize drilling processes for industrial applications.

The primary objectives of this study are twofold. First, the research seeks to thoroughly quantify the extent of peel-up and push-out delamination under varying drilling parameters, including cutting speeds ranging from 500 to 7500 Rpm, feed rates between 200 and 460 μm/rev, and drill bit diameters of 6, 8, and 10 mm. Second, leveraging the Taguchi method, the study aims to identify validated optimal drilling conditions that minimize delamination while balancing efficiency and precision. By addressing these objectives, the study aims to bridge the gap between theoretical knowledge and practical machining strategies, ultimately improving the reliability of thick GFRP composites in high-performance applications and contributing to sustainable manufacturing practices by reducing material wastage.

2. LITERATURE REVIEW

2.1. Overview of GFRC and its properties

GFRP composites are engineered materials comprising glass fibers embedded within a polymer matrix, typically thermoset resins such as epoxy or vinylester. These materials exhibit a synergistic combination of properties derived from their constituents: the glass fibers provide high tensile strength and stiffness, while the polymer matrix ensures load distribution, environmental protection, and dimensional stability (Sathishkumar et al., 2014; Mallick, 2007; Wallenberger et al., 2001). Key advantages of GFRP include a high strength-to-weight ratio, corrosion resistance, electrical insulation, and adaptability to complex geometries through advanced manufacturing techniques like VARTM (Campbell, 2003; Ahmed et al., 2023; Hoa, 2009). Despite these benefits, GFRP composites face challenges in machining, particularly drilling, due to their anisotropic structure and heterogeneous composition. Delamination, the separation of laminated layers, emerges as a critical defect during drilling, compromising structural integrity and leading to material rejection. This defect arises from the mismatch in mechanical behavior between the brittle glass fibers and the ductile polymer matrix under machining forces (Khashaba, 2009).

2.2. Drilling Methods for GFRP Composites

Drilling is a critical manufacturing process for GFRP composites, particularly in applications requiring precise assembly, such as aerospace, automotive, and defense systems. However, the heterogeneous and anisotropic nature of composites poses significant challenges during drilling, including delamination, fiber pull-out, and matrix degradation (Sheikh-Ahmad, 2009; Jessy et al., 2022). These defects compromise structural integrity and necessitate stringent control over machining parameters and methodologies. This section evaluates conventional and advanced drilling techniques, emphasizing their mechanisms, advantages, limitations, and influence on delamination (Kumar et al., 2022).

Conventional drilling (CD) employs rotary cutting tools, such as twist drills, to remove material through mechanical shearing. The process involves securing the workpiece to a drilling machine, where the rotating tool penetrates the composite under axial feed forces. While CD is cost-effective and widely accessible, its application to GFRP composites is troubled with challenges. The primary issue arises from the interaction between the drill bit and the laminated structure: high thrust forces and torque generated during drilling induce interlaminar stresses, leading to peel-up delamination at the entry and push-out delamination at the exit (Figure 2.1). Peel-up occurs when the rotational motion of the drill lifts the top layers, while push-out results from compressive forces fracturing the bottom layers (Davim et al., 2007).

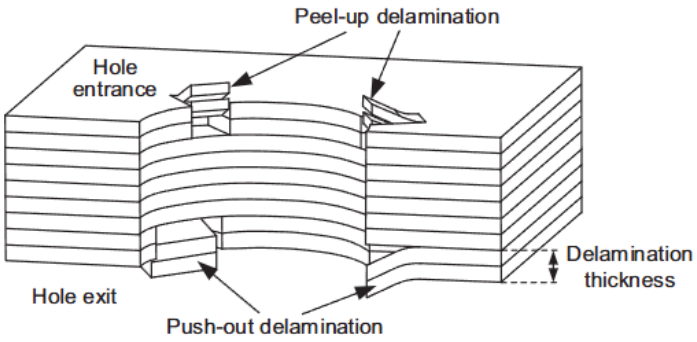


Figure 2.1. Peel-Up and Push-Out Delamination Mechanisms

Key parameters influencing CD include cutting speed, feed rate, and tool geometry. High feed rates amplify thrust forces, exacerbating delamination, whereas excessive cutting speeds generate frictional heat, degrading the polymer matrix. Tool wear further aggravates these issues, as dull edges increase cutting resistance. Studies by Kilickap (2010, 2011) demonstrated that optimizing drill geometry, using a 118° point angle and helical flutes, reduces stress concentration and improves chip evacuation, mitigating delamination. Despite these adjustments, CD remains suitable for high-precision applications in thick GFRP laminates due to inherent thermomechanical limitations.

Abrasive Water Jet Machining (AWJM) is a non-contact, non-thermal process that utilizes a high-velocity stream of water mixed with abrasive particles (e.g., garnet or aluminum oxide) to erode material. AWJM is advantageous for GFRP composites as it eliminates tool wear and minimizes heat-affected zones. The absence of direct mechanical contact reduces delamination risk, making it suitable for intricate geometries and thick laminates (Popan et al., 2022). The effectiveness of AWJM depends on parameters such as water pressure, stand-off distance, abrasive flow rate, and traverse speed. Excessive pressure or inadequate stand-off distance can cause kerf tapering or subsurface damage, while optimal settings yield clean cuts with minimal delamination (Vigneshwaran et al., 2018; Thongkaew et al., 2019). However, AWJM has limitations: it requires specialized equipment, generates significant noise, and produces slurry waste. Additionally, the process is less efficient for small-diameter holes due to jet divergence.

Laser drilling employs focused high-energy beams to vaporize material through localized heating. This method offers exceptional precision, enabling micron-level accuracy in hole geometry without mechanical contact. Pulsed laser systems are particularly effective for GFRP composites, as short-duration pulses minimize heat diffusion, reducing matrix carbonization and delamination (Singh et al., 2021; Cenna & Mathew, 2002; Choudhury et al., 2013). However, excessive energy input can degrade the resin, forming microcracks or charring. Trepanning, a technique where the laser beam circumscribes the hole perimeter, is often used for larger diameters to enhance edge quality (Baison Laser, 2023). Despite its precision, laser drilling is energy-

intensive and limited to thin laminates due to beam attenuation in thicker materials (Rao et al., 2019).

Electric Discharge Drilling (EDD) utilizes controlled electrical sparks to erode conductive materials. A dielectric fluid flushes debris and cools the workpiece, while the electrode advances axially to form the hole. EDD is advantageous for hybrid composites incorporating conductive fibers, as it avoids mechanical stresses (Roldan-Jimenez et al., 2022; Sheikh-Ahmad et al., 2016). However, applicability of EDD to non-conductive GFRP is limited unless a conductive coating is applied. Parameters such as voltage, current, and pulse duration must be carefully optimized: high currents increase material removal rates but risk surface cratering, while low currents enhance surface finish at the expense of efficiency.

2.3. Factors Affecting Delamination in GFRC During Drilling

Delamination, a critical defect arising during the drilling of composites, significantly compromises structural integrity and necessitates rigorous process optimization. This phenomenon manifests as interlaminar separation at the entry and exit regions of drilled holes, driven by mechanical and thermal stresses. The severity of delamination is governed by a complex interplay of process parameters, workpiece characteristics, and tool geometry, as illustrated in the fishbone diagram (Figure 2.2).

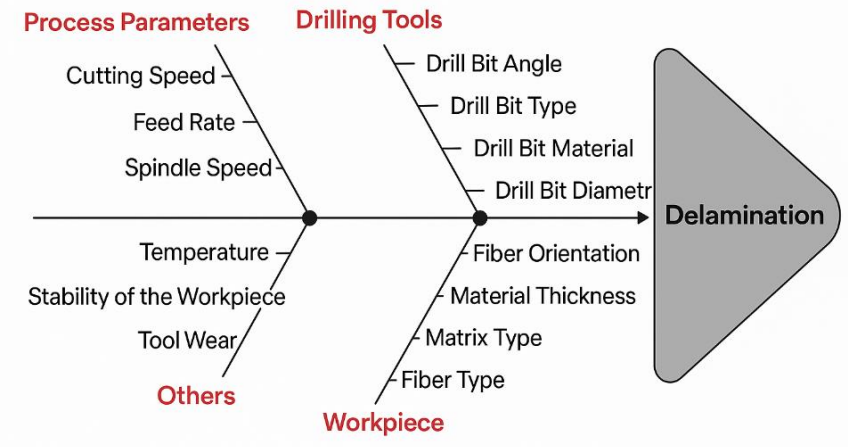


Figure 2.2. Root-Cause Analysis of GFRP Delamination

2.3.1. Process Parameters

Drilling parameters, including cutting speed, feed rate, and thrust force, exert a dominant influence on delamination dynamics. Cutting speed (V_c), defined as the peripheral velocity of the drill bit, directly impacts heat generation and mechanical loading (Figure 2.3). Higher cutting speeds reduce tool-material contact time, mitigating frictional heating and matrix degradation, thereby suppressing delamination (Davim, 2009; Karataş et al., 2018; Patel et al., 2018; Bayraktar, 2018). Conversely, low cutting speeds prolong thermal exposure, exacerbating resin softening and

interlaminar failure. Feed rate (V_f), the axial advancement of the drill per revolution, governs thrust force (F_z), a primary driver of delamination. Elevated feed rates amplify F_z, inducing higher compressive stresses at the drill exit, which propagate cracks between laminates (Kilickap, 2021). Babu et al. (2013-2022) observed a 35% increase in push-out delamination when feed rates rose from 200 to 460 µm/rev in GFRP composites. However, excessively low feed rates extend machining time, allowing heat accumulation and localized matrix degradation (Krishnaraj, 2008). Optimal feed rates thus balance thrust force reduction and thermal management.

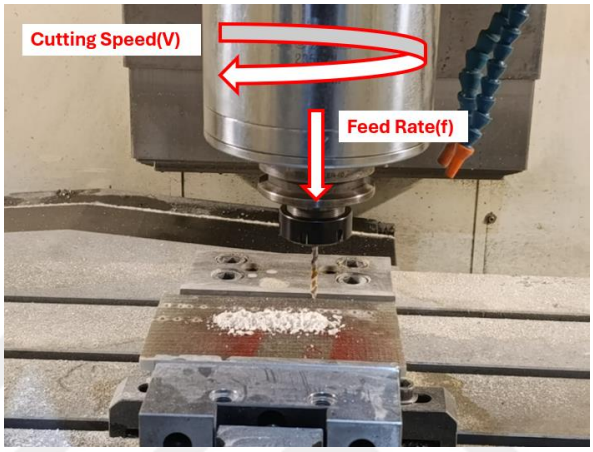


Figure 2.3. Drilling Parameter Interface.

Thrust force and torque (M_z) are further modulated by spindle speed (N) and drill diameter (D_{drill}). Empirical studies demonstrate a nonlinear relationship: $F_z \propto V_f^{0.8}$ and $M_z \propto D^{1.2}$ (Karnik et al., 2008). This underscores the need for parameter harmonization to minimize stress concentrations.

2.3.2. Workpiece Characteristics

The inherent anisotropy of GFRP composites, arising from alternating fiber and matrix layers, complicates uniform material removal. Fiber orientation, volume fraction, and laminate thickness significantly influence delamination susceptibility (Srivastava et al., 2021; Babu et al., 2020). Unidirectional fibers aligned parallel to the drill path exhibit higher resistance to peel-up delamination compared to woven architectures, which experience fiber pull-out at crossover points (Bekele et al., 2022).

Laminate thickness amplifies thermomechanical challenges. Thicker composites (≥10 mm) exhibit prolonged tool engagement, increasing heat retention and axial force transmission. Mohan et al (2007) reported a significant increase in the delamination factor when drilling 6 mm laminates with 10 mm thick GFRP under the same parameters. Additionally, resin-dominated regions in thick composites are prone to matrix cracking under cyclic loading, further exacerbating layer separation (Ahmed et al., 2023).

2.3.3. Drilling Equipment and Tool Geometry

The geometry of drilling tools plays a critical role in stress distribution and chip evacuation during the machining process. Key geometric factors include the point angle, helix angle, tool material, and drill diameter. A point angle of 118° minimizes stress concentration compared to sharper (90°) or blunter (135°) configurations, reducing peel-up delamination (Durao et al., 2010). A helix angle of 30° enhances chip flow efficiency, preventing clogging and secondary frictional heat generation (Chen, 1997). Carbide-coated drills exhibit superior wear resistance compared to High-Speed Steel (HSS) tools, maintaining cutting-edge sharpness and reducing thrust force (Arul et al., 2006). Drill diameter inversely correlates with delamination severity, as larger diameters distribute thrust forces over a broader contact area, lowering interfacial stresses. Yildirimci et al. (2024) and Bircan et al. (2024) observed delamination factors of 1.07 for 10 mm drills compared to 1.45 for 6 mm tools at higher cutting speed. However, oversized drills increase torque requirements, necessitating a balance between hole quality and energy efficiency.

2.3.4. Synthesis of Influencing Factors

Conflicting results in literature, such as the opposing effects of cutting speed reported by Kilickap (2011) and Baraheni et al. (2021), highlight the context-dependent nature of delamination. These discrepancies arise from variations in material composition, tool wear, and experimental setups. Bio-based resins exhibit lower thermal stability than conventional vinyl esters, altering optimal parameter windows (Benyettou et al., 2022).

The interplay of factors necessitates a systems approach. Taguchi-based optimization studies reveal that cutting speed contributes 52% to delamination effect, followed by feed rate and tool geometry (Palanikumar, 2011; Palanikumar et al., 2012). Real-time monitoring systems, integrating force and thermal sensors, further enable dynamic parameter adjustment to suppress delamination onset.

Table 2.1. Summary of Key Literature on GFRP Drilling-Induced Delamination

Studies	Materials	Parameters Used	Main Findings
Kilickap (2011)	GFRP	Cutting Speed, Feed Rate, and Point Angle	The specified parameters were optimized to reduce delamination.
Baraheni et al. (2021)	CDPF	Cutting Speed	Increasing cutting speed reduced the delamination level
Yildirimci et al. (2024)	GFRP	Feed Rate, Cutting Speed	Delamination is directly proportional to feed rate and inversely proportional to cutting speed.
Panneerselvam et al. (2014)	GFRP	Feed Rate, Spindle Speed	Delamination levels are minimum at high spindle speeds and low feed rates
Mohan et al. (2007)	GFRP	Cutting Speed and Material Thickness	Cutting speed and material thickness have a direct effect on de
Shunmugesh et al. (2017)	GFR	Cutting Speed, Feed Rate, Feed Ratio, and Tool Diameter	ANOVA results showed feed rate as the most influential parameter on overall performance.
Arul et al. (2006)	GFRP	Drill Bits	Tungsten carbide drill bits resulted in better hole quality compared to the other drill bits
Ramesh et al. (2014)	S-GFRP	Drill Bits Materials	Carbide bits showed minimal delamination compared to the other drill bits.
Durão et al. (2010)	CFRP	Drill Bits of Different Geometries	Drill bits with a 120° point angle produced the lowest delamination.

Existing research on the drilling optimization of GFRP composites has predominantly focused on thin laminates (≤5 mm thickness) and conventional cutting speeds (≤3000 Rpm). These studies have established foundational insights into delamination mechanisms, and parameter interactions in relatively thin composite structures (Khashaba, 2009-2010; Teti, 2002; Geier et al., 2019, 2023). Investigations by Palanikumar (2011) and Gaitonde et al. (2011) demonstrated that lower feed rates and moderate spindle speeds minimize delamination in thin GFRP sheets, primarily due to reduced axial forces and thermal degradation. However, contemporary industrial applications, particularly in aerospace, marine, and renewable energy sectors, increasingly demand the machining of thicker composites at elevated cutting speeds to enhance productivity and meet stringent performance requirements.

This shift toward thicker composites introduces unique challenges, as their thermomechanical responses during drilling differ significantly from those of thinner counterparts. Thicker laminates exhibit prolonged tool engagement, intensified heat accumulation, and complex stress distributions across multiple layers, all of which exacerbate delamination risks. Heat dissipation becomes less efficient in thick sections, leading to localized matrix softening and interfacial debonding, while cumulative thrust forces at deeper layers amplify push-out

delamination at the exit surface. Furthermore, conflicting findings persist regarding the effects of key parameters such as feed rate and spindle speed. Kilickap (2011) reported reduced delamination at lower feed rates GFRP, attributing this to diminished thrust forces. Conversely, Babu et al. (2022) observed higher delamination at identical feed rates in 8 mm laminates, suggesting that parameter optimizations for thin composites may not extrapolate to thicker configurations. Such discrepancies underscore the need for systematic investigations tailored to high-speed, thick-section drilling.

This study addresses these critical gaps by examining the drilling of 10 mm thick GFRP composites across a broad spectrum of cutting speeds (500–7500 Rpm) and feed rates (200–460 μm/rev). The research objectives are:

- Quantify Delamination: Evaluate peel-up and push-out delamination using optical microscopy and the delamination factor.
- Optimize Parameters: Employ the Taguchi method, a robust Design-Of-Experiments (DoE) approach, to identify optimal combinations of cutting speed, feed rate, and drill bit diameter (6–10 mm). This method minimizes experimental trials while statistically isolating the influence of each parameter on delamination.

3. MATERIAL AND METHOD

This study investigates delamination formation during the drilling of thick GFRP composites and identifies optimal machining parameters. The following sections detail the materials, manufacturing processes, experimental setup, and methodologies employed.

3.1. Material Fabrication

GFRP composites are engineered materials comprising a polymer matrix reinforced with glass fibers, offering a balance of mechanical performance, corrosion resistance, and cost-effectiveness. The constituent materials selected for this study include Metyx GW300 unidirectional glass fiber as the reinforcement phase and Crystic VE 679-03PA vinylester resin as the matrix. These materials were chosen based on their compatibility, industrial relevance, and suitability for manufacturing technique.

The reinforcement phase consists of Metyx GW300 glass fiber fabric, characterized by its high tensile strength, moderate stiffness, and resistance to environmental degradation. The properties of the glass fiber, as provided by the manufacturer and verified through standardized testing, are summarized in Table 3.1. The fabric exhibits an areal density of 306 g/m², ensuring uniform reinforcement distribution, while its tensile strength of 3,450 MPa and Young's modulus of 72 GPa make it suitable for structural applications requiring load-bearing capacity. Crystic VE 679-03PA vinylester resin was selected as the matrix due to its superior adhesion to glass fibers, low viscosity, and rapid curing characteristics. The mechanical properties of the resin, detailed in Table 3.2, include a tensile strength of 90 MPa and flexural strength of 150 MPa, providing dimensional stability and effective load distribution. The elongation at break of 4–6% ensures ductility, mitigating brittle failure under dynamic loading. To initiate polymerization, Akperox mA60 MEK-P (methyl ethyl ketone peroxide) was added as a catalyst at 1.5% by weight of the resin.

Table 3.1. Mechanical and Physical Properties of Glass Fiber Reinforcement

Properties	**Glass**
	Metyx GW300
Areal Density (g/m^2)	306
Density (g/cm^3)	2.55
Tensile Strength (MPa)	3450
Young's Modulus (GPa)	72
Elongation at Break (%)	4.8
Fiber Diameter (Microns)	9 – 13

Table 3.2. Thermomechanical Properties of Vinylester Resin Matrix

Properties	Vinylester
	Crystic VE 679-03PA
Density (g/cm³)	1.06
Viscosity [mPa·s (at 25°C)]	250 – 450
Gel Time (minutes)	20 – 30
Tensile Strength (MPa)	90
Flexural Strength (MPa)	150
Elongation at Break (%)	4 – 6

The GFRP laminates used in this study were fabricated in-house at Secant Technology Development Inc. using a Vacuum-Assisted Resin Infusion process, which ensures uniform resin distribution and minimizes material waste. The vacuum-assisted resin infusion method was selected for its ability to produce large, complex parts with minimal void content and consistent fiber-to-resin ratios. This method not only reduces material waste but also enhances the mechanical integrity of the final product by ensuring homogeneous resin distribution throughout the laminate (Figure 3.1).

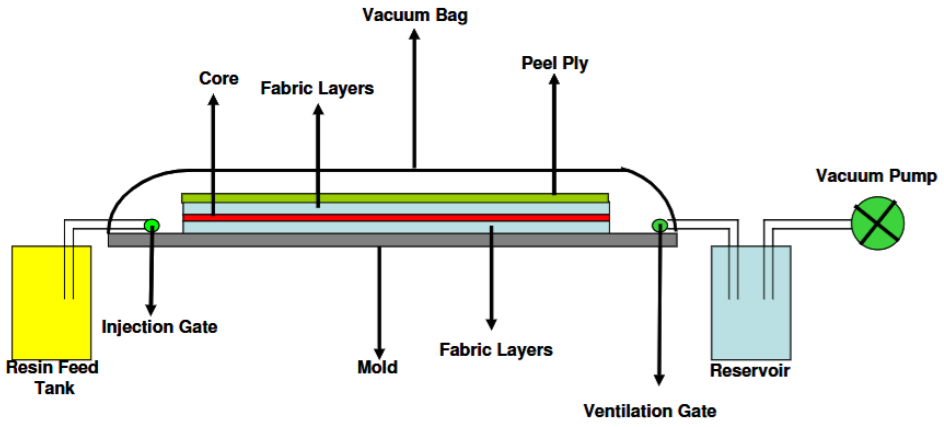


Figure 3.1 Vacuum-Assisted Resin Infusion Process Setup

The composite laminates were designed with a fiber volume fraction of 81% and a resin content of 19%, aligning with industry standards for structural GFRP applications. The required quantities of fiber, resin, and catalyst were calculated based on the laminate dimensions (200 cm³ volume) and constituent densities. The total mass of the composite was derived using the rule of mixtures:

$\rho_{Total} = (0.81 \times 2.55) + (0.19 \times 1.06) = 2.2669\ g/cm^3$

$m_{Total} = \rho_{Total} \times V = 2.2669\ g/cm^3 \times 200 cm^3 = 453.38\ g$

Subsequently, the mass of each constituent was determined:

m_{Fiber}=0.81×453.38=367.24 g

m_{Matrix}=0.19×453.38=86.14 g

$m_{Catalyst}$=0.015×86.14=2.67 g

The fabrication process began with the preparation of 21 layers of glass fiber, each cut to dimensions of 100 × 200 mm. The mold surface was meticulously cleaned with ethanol and coated with XTEND-1140HS mold release agent to facilitate demolding and achieve a smooth surface finish. The fiber layers were then stacked sequentially on the mold, followed by the application of a peel ply to prevent adhesion between the composite and the vacuum bag. A flow mesh was incorporated to enhance resin distribution, and a spiral tube was positioned to regulate resin flow during infusion.

The vacuum bag was sealed over the assembly, and the system was checked for leaks before initiating the vacuum process. Resin was introduced under vacuum pressure, ensuring complete impregnation of the fiber layers. The curing process was conducted in a controlled oven environment to achieve optimal polymerization. Post-curing, the edges of the laminates were trimmed to remove excess material and burrs, resulting in flat, uniform panels with a final thickness of 10 mm (Figure 3.3).

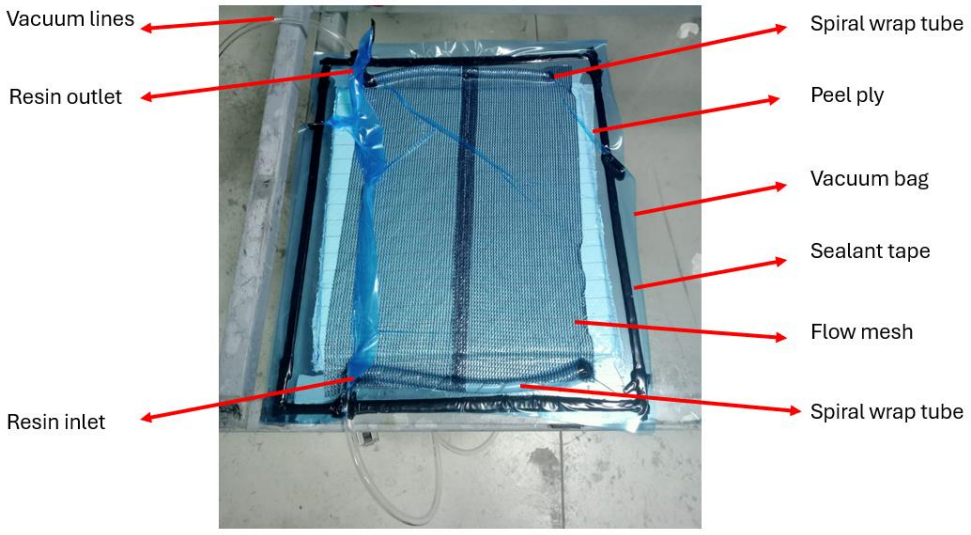


Figure 3.2. In-Process Vacuum-Assisted Resin Infusion Layup

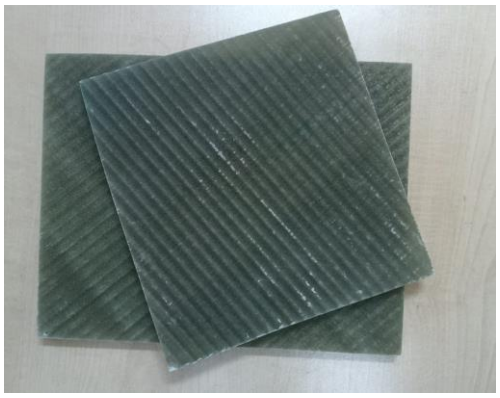
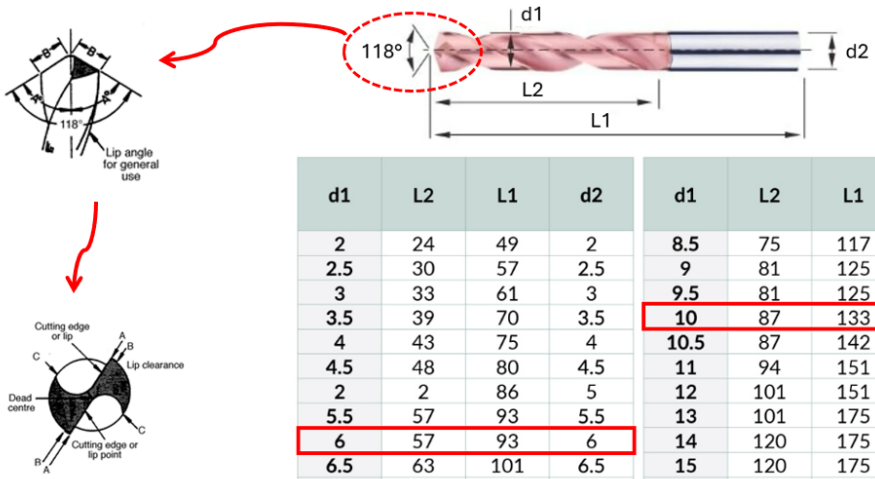


Figure 3.3. GFRP Laminate Specimen Preparation

The mechanical properties of the fabricated GFRP were validated through tensile testing in accordance with ASTM D3039.

3.2. Drilling Equipment

The selection of appropriate cutting tools and machining equipment is critical in minimizing drilling-induced delamination in thick GFRP composites. Three tungsten carbide drill bits with diameters of 6 mm, 8 mm, and 10 mm were used (Figure 3.4). Tungsten carbide tools were selected due to their superior wear resistance, high hardness, and ability to maintain sharp cutting edges under elevated temperatures, as demonstrated by Arul et al. (2006), who reported a 25% reduction in thrust force compared to HSS tools. Each drill bit featured a 118° point angle and a 30° helix angle, geometries optimized to balance stress distribution and chip evacuation. These design choices align with prior studies emphasizing the role of tool geometry in delamination suppression (Khashaba et al., 2010).



d1	L2	L1	d2	d1	L2	L1	d2
2	24	49	2	8.5	75	117	8.5
2.5	30	57	2.5	9	81	125	9
3	33	61	3	9.5	81	125	9.5
3.5	39	70	3.5	10	87	133	10
4	43	75	4	10.5	87	142	10.5
4.5	48	80	4.5	11	94	151	11
2	2	86	5	12	101	151	12
5.5	57	93	5.5	13	101	175	13
6	57	93	6	14	120	175	14
6.5	63	101	6.5	15	120	175	15
7	69	109	7	16	120	175	16
7.5	69	109	7.5	18	120	175	18
8	75	117	8	20	120	175	20

Figure 3.4. Carbide drill bits used.

Drilling experiments were conducted on a JohnFord VMC-550A CNC vertical machining center (Figure 3.5), chosen for its precision, rigidity, and adaptability to composite machining. The machine operates within a spindle speed range of 60–6,000 rpm, enabling cutting speeds up to 7,500 Rpm for the 10 mm drill bit. A feed rate range of 0–4,000 mm/min allowed precise control over axial thrust forces, a critical factor in delamination dynamics. The CNC system incorporated closed-loop feedback control, ensuring positional accuracy within ±5 μm, which is essential for repeatability in high-speed drilling. No cooling fluid was employed during operations to avoid matrix hydrolysis, a common issue with thermoset resins. Instead, dry machining conditions were maintained, necessitating severe parameter optimization to counteract frictional heat generation.



Figure 3.5. CNC vertical machining center used for drilling operations.

The GFRP specimens were securely clamped to the machine bed using a fixture to prevent vibration-induced damage. A sacrificial backing plate of Medium-Density Fiberboard (MDF) was positioned beneath the composite to minimize push-out delamination during drill exit (Figure 3.6). This setup reduced unsupported laminate deflection, a key contributor to interlaminar fracture. Tool runout was measured prior to each experiment using a dial indicator, ensuring alignment within 10 μm to avoid eccentric loading. Spindle speed and feed rate combinations were programmed in accordance with the Taguchi L27 orthogonal array, covering five cutting speeds (500–7,500 Rpm) and three feed rates (200–460 μm/rev) per drill diameter.

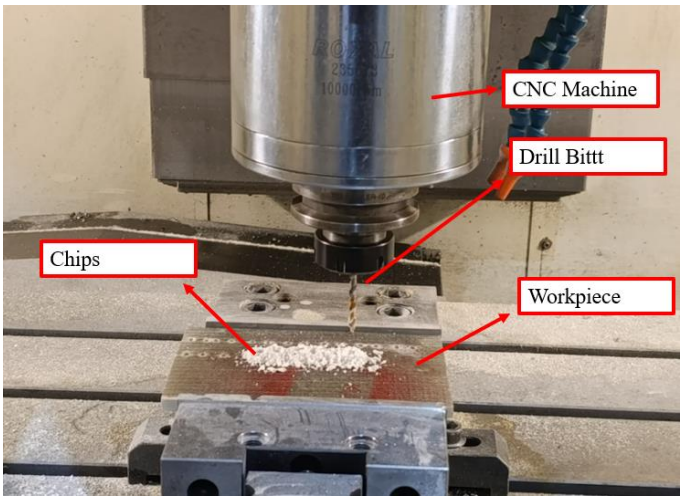


Figure 3.6. Workpiece Fixturing for Drilling

3.3. Measurement Instruments

Accurate evaluation of delamination damage in composite materials necessitates the use of precision measurement tools capable of resolving micron-scale defects. In this study, a combination of advanced optical microscopy and digital image analysis was employed to evaluate peel-up and push-out delamination. The primary instrument utilized for damage assessment was the Nikon Eclipse L150 optical microscope (Figure 3.7), selected for its high-resolution imaging capabilities and compatibility with composite material analysis. This microscope features bright-field and dark-field illumination modes, enabling detailed observation of surface defects. With a magnification range of 5× to 50× and a resolution of 1 µm, the system allowed for precise measurement of delamination zones at the entry and exit surfaces of drilled holes.


Figure 3.7. Optical microscope used for delamination measurement.

3.4. Drilling Parameters and Experimental Design

Drilling operations in GFRP composites necessitate precise control over machining variables to lessen delamination, a critical defect compromising structural integrity. This study investigated three primary parameters: cutting speed, feed rate, and drill bit diameter. Cutting speeds ranged from 500 to 7500 Rpm, feed rates from 200 to 460 µm/rev, and drill diameters of 6,

8, and 10 mm (Table 3.3). These ranges were selected to evaluate delamination behavior across industrial-relevant high-speed conditions. The selected cutting speed range (500–7,500 Rpm) addresses a gap in existing literature, which predominantly focuses on speeds below 3,000 Rpm for thin laminates (Mohan et al., 2007). High-speed drilling was included to evaluate its potential for reducing thermal degradation through shorter tool-material contact times. Feed rates were constrained to 200–460 μm/rev to balance productivity and delamination risk, with lower rates minimizing thrust forces and higher rates simulating industrial efficiency demands (Babu et al., 2022). The drill diameters (6–10 mm) reflect common hole sizes in aerospace and marine applications, where thicker composites require larger fasteners (Ahmed et al., 2023).

Table 3.3. Experimental Drilling Parameters for GFRP

Cutting speed (Rpm)	500	L1
	1000	L2
	1500	L3
	5000	L4
	7500	L5
Feed rate (μm/rev)	200	L1
	380	L2
	460	L3
Drill diameter (mm)	6	L1
	8	L2
	10	L3

3.5. Delamination and Calculation of Delamination Factor

Delamination represents one of the most critical failure modes in composite machining, frequently leading to component rejection due to compromised structural integrity and reduced fatigue resistance (Davim et al., 2007; Liu et al., 2019). This defect manifests as interlaminar separation between plies during drilling operations, primarily occurring at two distinct locations:

1. Peel-Up Delamination: Observed at the drill entry point, where the rotational motion of the drill bit generates upward tensile forces that lift and separate the topmost composite layers.
2. Push-Out Delamination: Occurs at the exit point, resulting from axial compressive forces that fracture and displace the bottommost plies (Kumar et al., 2022).

Both mechanisms arise from the anisotropic nature of GFRP composites, wherein the brittle reinforcement fibers and ductile polymer matrix exhibit divergent responses to machining stresses. This mismatch induces interfacial debonding, significantly diminishing load-bearing capacity and long-term durability (Hocheng & Tsao, 2006).

The delamination factor (F_d) serves as a standardized metric to quantify damage severity. It is defined as the ratio of the maximum observed damage diameter (D_{max}) to the nominal drill diameter (D_{drill}), and calculated using Equation 1:

$$F_d = \frac{D_{max}}{D_{drill}} \quad \text{Eq.1}$$

A value of F_d=1.0 indicates an absence of delamination, while higher values denote progressive damage severity (Rao et al., 2024). Figure 3.8. illustrates these mechanisms, and Figure 3.9. provides visual evidence of D_{max} measurements in GFRP laminates.

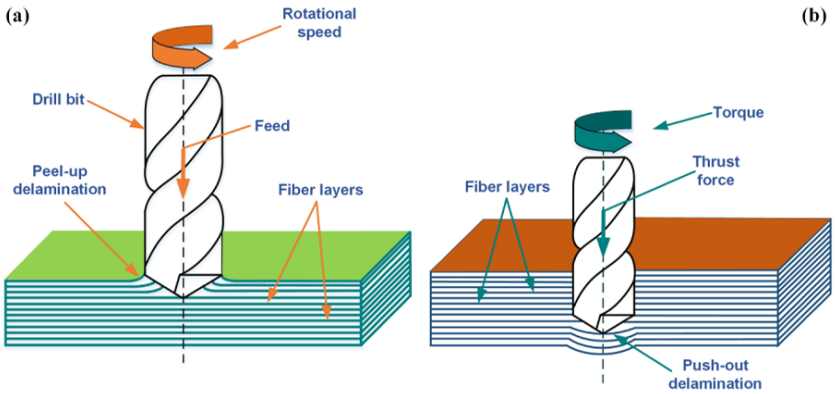


Figure 3.8. Mechanisms of delamination: (a) peel-up at entrance and (b) push-out at exit (Kumar, et al 2022).



Figure 3.9. Measurement methodology for F_d: (a) Literature schematic (Rao et al., 2024); (b) Experimental observation on GFRP.

Experimental measurement followed a rigorous protocol. Over 100 holes were drilled in 10-mm-thick GFRP laminates using a CNC vertical machining center, with each parameter combination replicated twice for statistical validity. Entry and exit surfaces underwent examination via optical microscopy at 20× magnification. Three radial measurements were taken at the most severely damaged zone, with the average computed to minimize measurement bias. The F_d was calculated using Eq. 1 and averaged across replicates to yield $F_{d,ave}$.

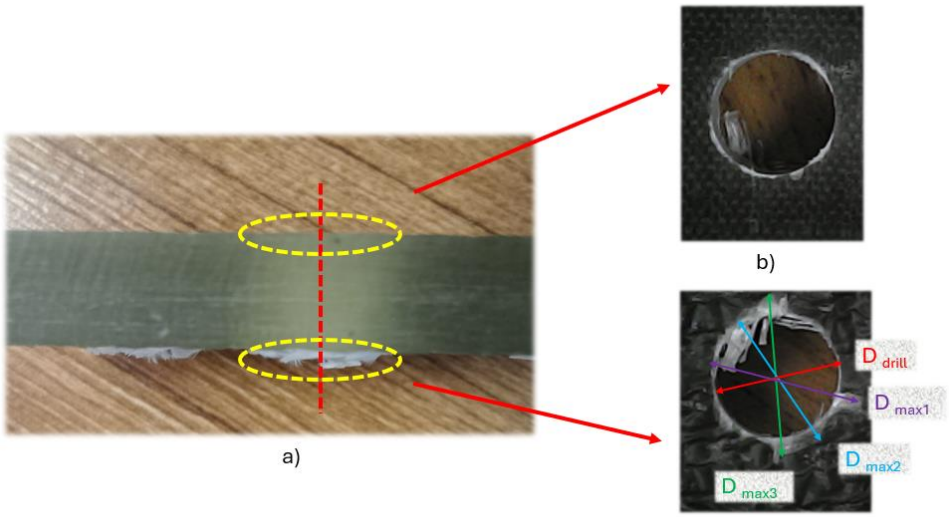


Figure 3.10. Representation on Drilled GFRP Material a) Side View, b) Peel-Up, c) Push-out

3.6. Taguchi Analysis and Signal-to-Noise Ratios

The Taguchi method, a robust DoE approach, was employed to minimize experimental trials while isolating parameter effects (Montgomery, 1991; Ross, 1996). Signal-to-noise (S/N) were computed using the "smaller-is-better" criterion (Equation 2):

$$\eta = -10\ log10\ [\frac{1}{n}\Sigma_{i=1}^{n} y_i^2] \qquad \text{Eq.2}$$

Here, y_i denotes the measured F_d, and η reflects parameter robustness against delamination. Higher η values indicate superior performance. Data were analyzed in Minitab 18 to derive S/N response tables.

The experimental workflow (Figure 3.11) encompassed material fabrication, CNC drilling, microscopic measurement, and statistical analysis. This integrated approach ensured systematic parameter optimization and validated the reproducibility of results across industrial applications.

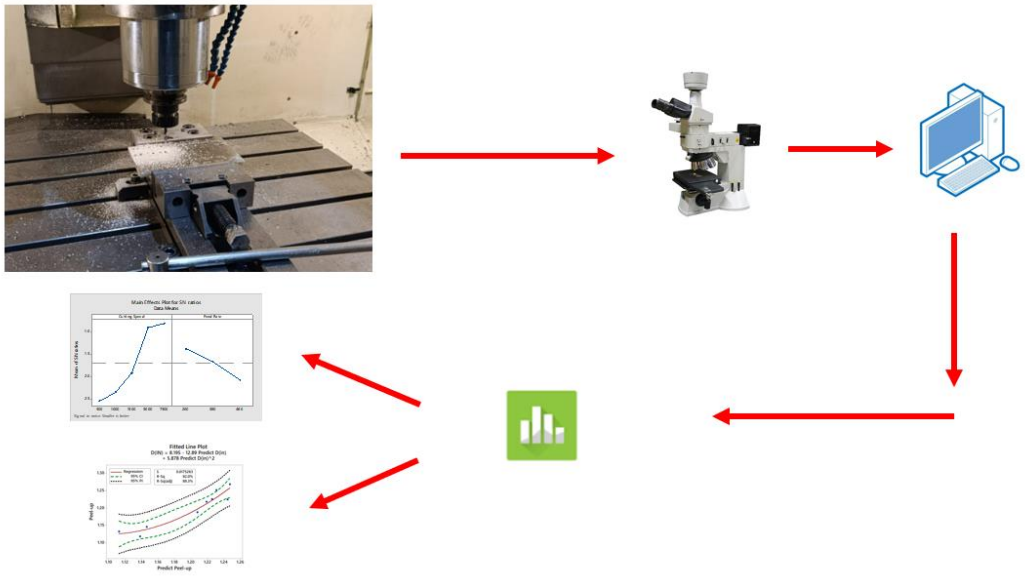


Figure 3.11. Schematic of the experimental workflow for drilling and delamination analysis.

4. RESULTS AND DISCUSSIONS

4.1. Material Characterization and Mechanical Properties

Prior to drilling experimentation, the mechanical properties of the fabricated 10 mm thick GFRP composites underwent comprehensive characterization through standardized testing protocols. This basic analysis established structural integrity and consistency of the material, providing essential for interpreting drilling-induced damage mechanisms.

Tensile testing according to ASTM D3039 was performed on five specimens, with the resulting stress-strain relationship depicted in Figure 4.1. The composite exhibited characteristic linear elastic deformation until catastrophic failure, with negligible plastic yielding, a signature behavior of fiber-dominant polymer composites. As detailed in Table 4.1, the material demonstrated a mean tensile strength of 378.12 MPa, with specimen-specific values ranging from 362.28 MPa to 395.00 MPa. The elastic modulus, calculated within the 0.1-0.3% strain range, averaged 26.13 GPa with minimal variation. The failure strain exhibited a mean value of 2.46% (SD: ±0.15%), confirming the limited ductility consistent with high fiber-volume fraction (81%) architectures. Poisson's ratio remained remarkably consistent across specimens (μ=0.13, SD=±0.007), reflecting the anisotropic nature inherent to unidirectional fiber reinforcement.

The exceptionally low standard deviations observed across all properties (<5% coefficient of variation) confirm higher manufacturing consistency achieved through vacuum-assisted resin infusion process. This process uniformity is particularly evident in thickness measurements and fiber distribution. The mechanical profile aligns with aerospace-grade GFRP benchmarks documented by Sathishkumar et al. (2014), with tensile strength variations attributable to localized fiber misalignment during layup.

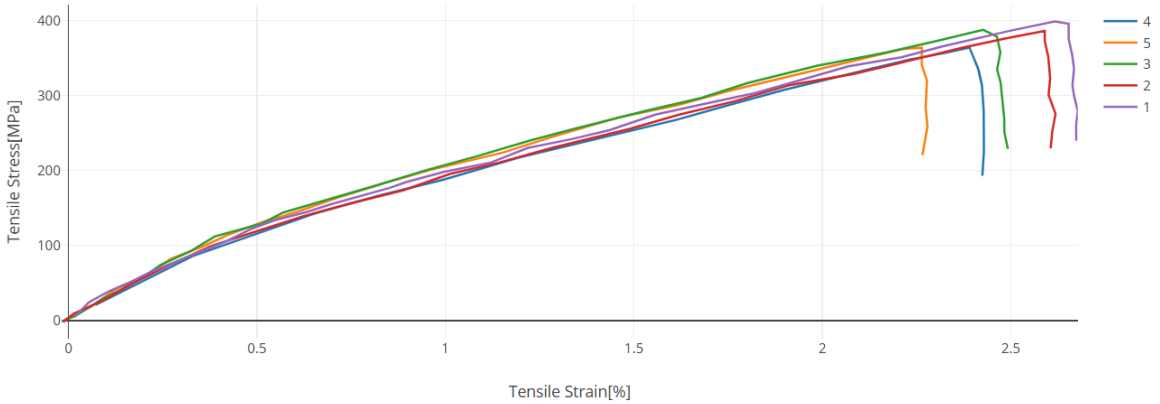


Figure 4.1. Tensile Stress-Strain Behavior of GFRP

Table 4.1. Tensile Properties of Fabricated 10-mm GFRP Laminate (ASTM D3039)

Sample	Length (mm)	Thickness (mm)	Width (mm)	Modulus (GPa)	Poisson's ratio	Maximum Tensile stress (MPa)	Maximum Tensile strain (%)
S1	150	2.56	25.04	25.3198	0.12	395	2.61373
S2	150	2.46	25.19	27.4283	0.14	364.704	2.25153
S3	150	2.59	25.19	24.9133	0.13	362.276	2.3864
S4	150	2.58	25.09	25.395	0.13	383.125	2.57862
S5	150	2.54	25.23	27.6085	0.14	385.494	2.44872
Mean	150	2.55	25.15	26.133	0.13	378.12	2.4558
Standard deviation	0	0.05177	0.0795	1.27951	0.00653	14.10109	0.14716

4.2. Delamination Analysis

4.2.1. Delamination Analysis for 6 mm Drill Diameter

The drilling of 10 mm thick GFRP composites with a 6 mm diameter drill bit revealed critical insights into delamination mechanisms under varying machining parameters. As documented in Table 4.2, push-out delamination consistently exceeded peel-up delamination across all parameter combinations. At a cutting speed of 500 Rpm and feed rate of 200 μm/rev, push-out delamination (1.7370) was 35.7% higher than peel-up delamination (1.2801). This phenomenon stems from fundamental stress dynamics: compressive forces dominate at the drill entry, while tensile stresses prevail at the exit. The anisotropic nature of GFRP composites amplifies this effect, as the polymer matrix exhibits lower resistance to tensile stresses, resulting in more severe interlaminar separation at the bottom layers.

Table 4.2. Measured Peel-up and Push-out delamination factors for 6 mm diameter drill.

Diameter	Cutting Speed	Feed Rate	Peel-up Delamination	Push-out Delamination	S/N (Peel-up)	S/N (Push-out)
6	500	200	1.2801	1.7370	-2.144	-4.795
6	500	380	1.2941	1.6688	-2.237	-4.447
6	500	460	1.4518	2.0182	-3.234	-6.098
6	1000	200	1.2868	1.3954	-2.194	-2.894
6	1000	380	1.2382	1.4767	-1.858	-3.385
6	1000	460	1.4099	1.6397	-2.984	-4.297
6	1500	200	1.1184	1.2519	-0.971	-1.943
6	1500	380	1.3391	1.4056	-2.535	-2.955
6	1500	460	1.2938	1.4628	-2.235	-3.307
6	5000	200	1.0981	1.2298	-0.812	-1.796
6	5000	380	1.1038	1.1831	-0.858	-1.461
6	5000	460	1.1291	1.2681	-1.052	-2.065
6	7500	200	1.0913	1.4042	-0.756	-2.943
6	7500	380	1.1021	1.3568	-2.144	-4.795
6	7500	460	1.1014	1.3201	-2.237	-4.447

Feed rate emerged as a primary frustrate of delamination. When cutting speed was held constant at 500 Rpm, increasing the feed rate from 200 to 460 μm/rev elevated peel-up delamination by 13.4% and push-out delamination by 16.1%. This correlation arises from the direct relationship between feed rate and thrust force, where higher feed rates increase axial compressive stresses, impairing layer separation. Conversely, cutting speed demonstrated a mitigating effect. At a fixed feed rate of 460 μm/rev, increasing cutting speed from 500 to 7500 Rpm reduced peel-up delamination by 24.1% and push-out delamination by 34.6%. This improvement occurs because higher cutting speeds reduce tool-material contact time, minimizing frictional heat generation and associated matrix degradation.

Optical micrographs provided visual validation of these trends. Figure 4.2. illustrates peel-up damage characterized by localized fiber-matrix debonding, while Figure 4.3 shows extensive push-out delamination with radial crack propagation. Figure 4.4 further highlights the worst-case scenario at 500 Rpm and 460 μm/rev, where push-out delamination extended 2.18 times the nominal drill diameter, severely compromising structural integrity.

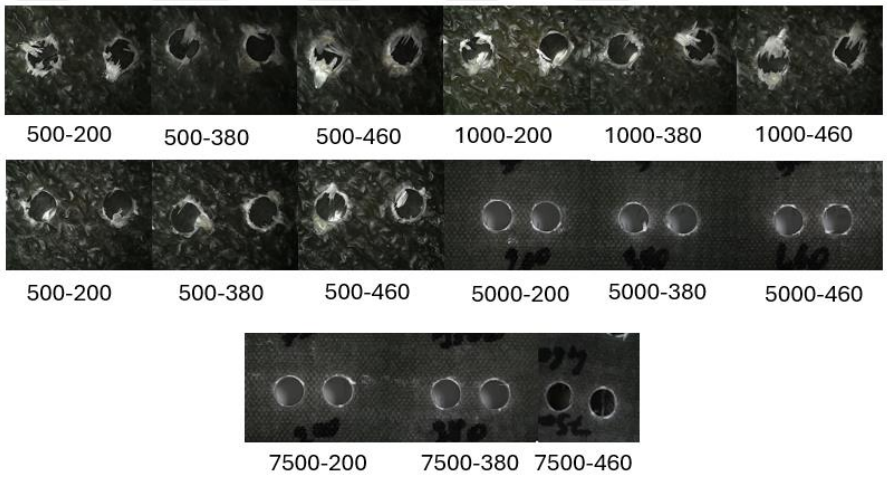


Figure 4.2. Peel-Up Delamination Morphology (Ø6 mm Drill)

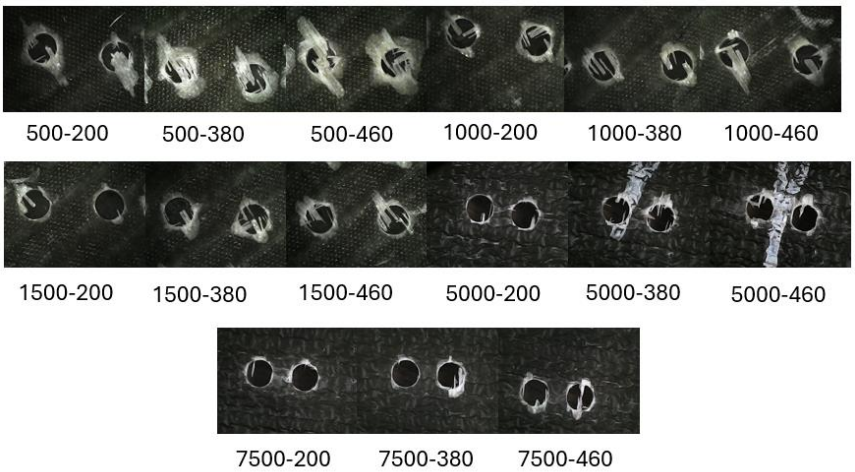


Figure 4.3. Push-Out Delamination Morphology (Ø6 mm Drill)

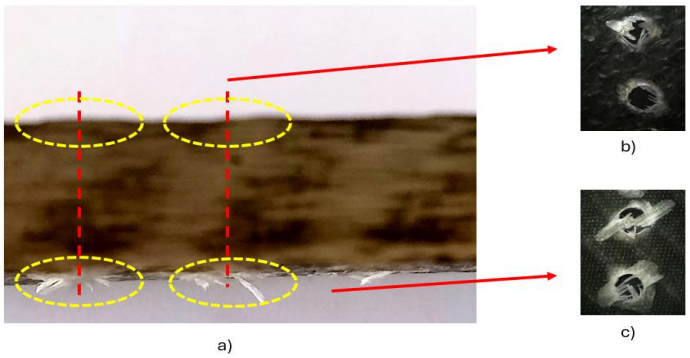


Figure 4.4. Severe Delamination Under Aggressive Drilling (Ø6 mm Drill); a) Side View, b) Peel-up, c) Push-out

Taguchi optimization quantified parameter dominance through S/N (Table 4.3). Cutting speed exhibited the strongest influence on peel-up delamination (δ = 1.7267, Rank 1), with optimal performance at 7500 Rpm. Feed rate ranked second, with minimal delamination at 200 µm/rev. For push-out delamination (Table 4.4), cutting speed again dominated, though the optimal level shifted to 5000 rather than 7500 Rpm. This deviation suggests thermal anomalies at ultra-high speeds, where excessive heat may soften the matrix despite reduced contact time. Figure 4.5. graphically confirms that push-out damage increased by 41.2% when feed rate rose from 200 to 460 µm/rev at low cutting speeds.

Table 4.3. S/N Ratios for Peel-up Delamination (Ø6 mm Drill).

Level	Cutting Speed	Feed Rate
1	-2.5408	-1.3758
2	-2.3431	-1.6667
3	-1.9151	-2.0704
4	-0.9084	
5	-0.8141	
Delta	1.7267	0.6946
Rank	1	2

Table 4.4. S/N Ratios for Push-out Delamination (Ø6 mm Drill).

Level	Cutting Speed	Feed Rate
1	-5.115	-2.877
2	-3.525	-2.98
3	-2.737	-3.635
4	-1.773	
5	-2.67	
Delta	3.341	0.757
Rank	1	2

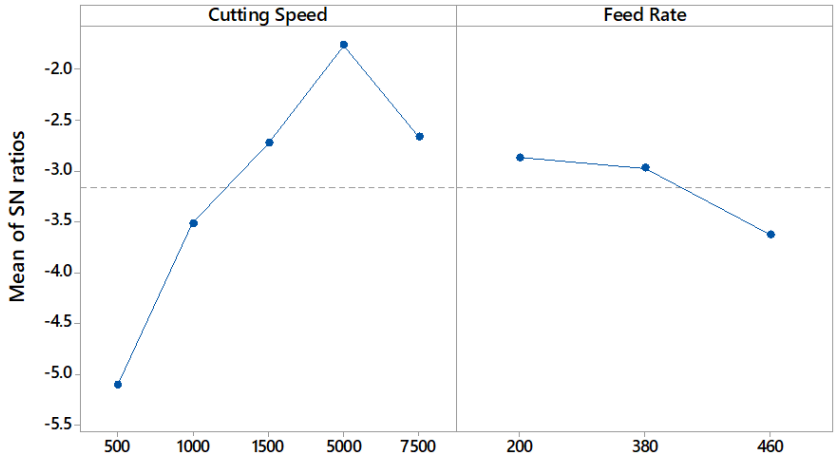


Figure 4.5. S/N versus cutting speed and feed rate for Peel-up delamination (Ø6 mm Drill).

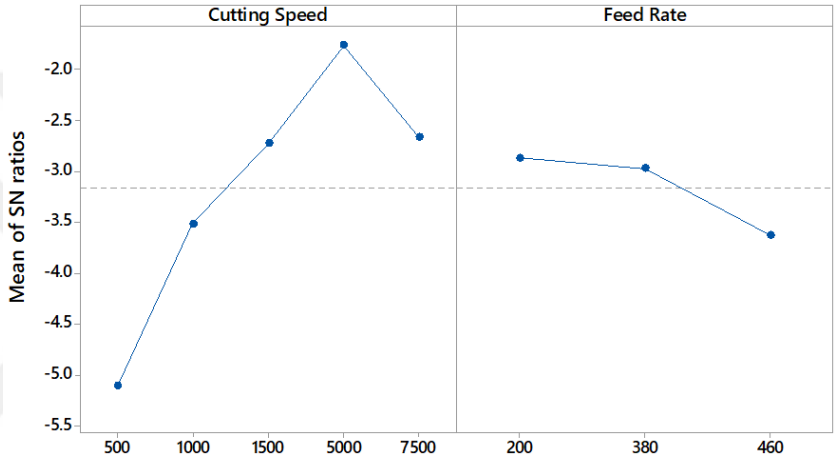


Figure 4.6. S/N versus cutting speed and feed rate for Push-out delamination (Ø6 mm Drill).

These results underline the vulnerability of small-diameter (6 mm) drilling operations to exit-plane delamination, particularly under low-speed/high-feed conditions. The concentrated stress distribution and limited chip evacuation capacity of smaller tools amplify this susceptibility, necessitating stringent parameter control for precision applications.

4.2.2. Delamination Analysis for 8 mm Drill Diameter

The drilling of GFRP composites with 8 mm diameter tools revealed distinct delamination behaviors under varying machining parameters, as quantified in Table 4.5. Push-out delamination consistently exceeded peel-up damage across all parameter combinations, with the most severe case occurring at the lowest cutting speed and highest feed rate. This phenomenon stems from the interplay of mechanical and thermal mechanisms: compressive stresses dominate at the drill entry, while tensile stresses at the exit plane exacerbate interlaminar separation in lower layers of the composite. Notably, increasing cutting speed from 500 to 7500 Rpm reduced average peel-up delamination by 32.7%, corroborating the hypothesis that reduced tool-material contact time

minimizes frictional heating and matrix degradation. Conversely, elevating feed rates from 200 to 460 μm/rev amplified peel-up delamination by 10.8% due to proportional increases in thrust forces.

Table 4.5. Measured Peel-up and Push-out delamination factors for 8 mm diameter drill bit.

Diameter	Cutting Speed	Feed Rate	Peel-up Delamination	Push-out Delamination	S/N (Peel-up)	S/N (Push-out)
8	500	200	1.3035	1.2495	-2.299	-1.938
8	500	380	1.3479	1.2621	-2.595	-2.023
8	500	460	1.4439	1.4384	-3.194	-3.160
8	1000	200	1.2069	1.2833	-1.633	-2.170
8	1000	380	1.2592	1.2566	-2.007	-1.992
8	1000	460	1.2708	1.2877	-2.086	-2.201
8	1500	200	1.1428	1.1966	-1.160	-1.555
8	1500	380	1.1448	1.2129	-1.175	-1.679
8	1500	460	1.2402	1.2282	-1.867	-1.787
8	5000	200	1.0993	1.2658	-0.822	-2.049
8	5000	380	1.1753	1.2622	-1.399	-2.024
8	5000	460	1.2480	1.2827	-1.915	-2.163
8	7500	200	1.0983	1.1489	-0.813	-1.203
8	7500	380	1.0704	1.2580	-0.593	-2.007
8	7500	460	1.1381	1.2948	-1.123	-2.244

Visual evidence from optical microscopy (Figures 4.7 and 4.8) substantiated these trends. Specimens drilled at 5000 m/min exhibited notably cleaner hole peripheries, with peel-up zones showing only marginal fiber-matrix debonding. This aligns with the thermal degradation threshold theory proposed by Chen (1997), wherein speeds exceeding 3000 m/min prevent resin softening through adiabatic heating. The worst-case delamination scenario (Figure 4.10) occurred at 500 m/min and 460 mm/rev, where excessive thrust forces and prolonged thermal exposure caused pronounced layer separation, evidenced by radial cracks extending 1.43× beyond the nominal hole diameter.

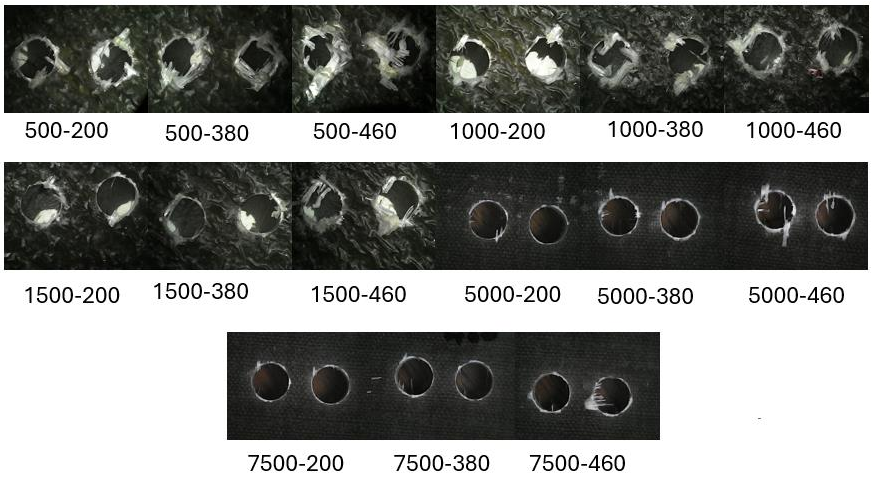


Figure 4.7. Peel-Up Delamination Morphology (Ø8 mm Drill)

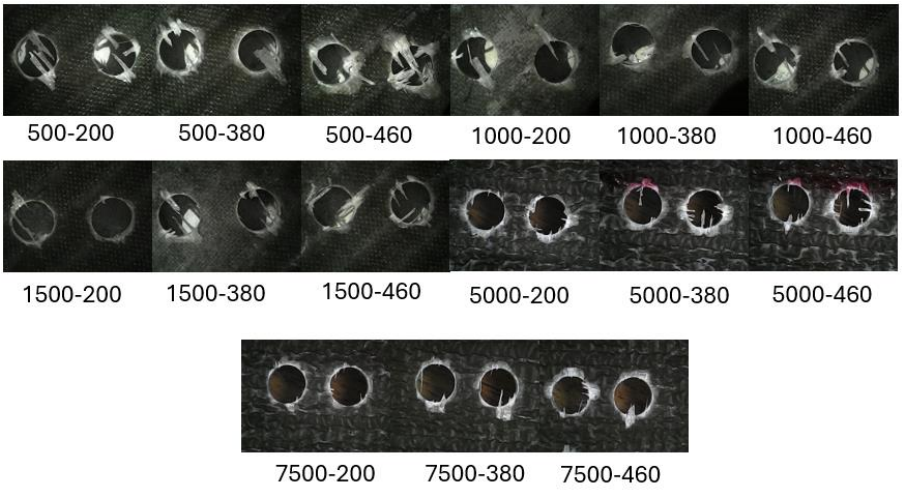


Figure 4.8. Push-Out Delamination Morphology (Ø8 mm Drill)

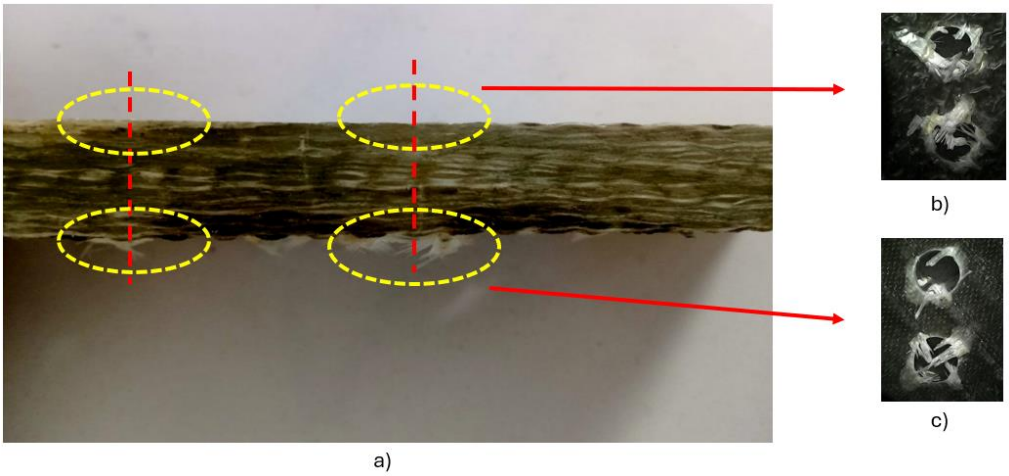


Figure 4.9 Severe Delamination Under Aggressive Drilling (Ø8 mm Drill); a) Side View, b) Peel-up, c) Push-out

The Taguchi-based optimization for 8 mm drilling established cutting speed as the dominant factor governing peel-up delamination ($\delta = 1.8526$, Table 4.6). The S/N response surface (Figure 4.10) confirmed that 7500 Rpm minimized peel-up damage, while 200 µm/rev feed rate provided secondary optimization. This finding challenges earlier studies on thin laminates (Palanikumar, 2011), which recommended moderate speeds but did not account for heat accumulation in thick-section composites.

Table 4.6. S/N Ratios for Peel-up Delamination (Ø8 mm Drill).

Level	Cutting Speed	Feed Rate
1	-2.6954	-1.3462
2	-1.9057	-1.5526
3	-1.4011	-2.0379
4	-1.383	
5	-0.8427	
Delta	1.8526	0.6917
Rank	1	2

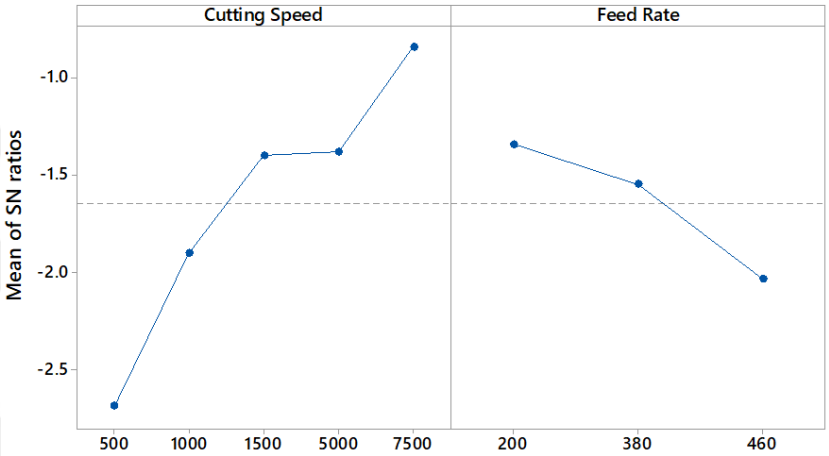


Figure 4.10. S/N versus cutting speed and feed rate for Peel-up delamination (Ø8 mm Drill).

For push-out delamination (Table 4.7), cutting speed remained influential ($\delta = 0.698$, Rank 1), though its dominance diminished compared to peel-up. The nonlinear S/N relationship (Figure 4.11) revealed an anomaly at 5000 Rpm, where delamination exceeded values at both lower (1500 Rpm and higher (7500 Rpm) speeds. This suggests a critical thermomechanical transition zone where residual stresses from rapid heating-cooling cycles counteract the benefits of reduced contact time, a phenomenon previously unreported in literature.

Table 4.7. S/N Ratios for Push-out Delamination (Ø8 mm Drill).

Level	Cutting Speed	Feed Rate
1	-2.371	-1.783
2	-2.116	-1.94
3	-1.674	-2.309
4	-2.078	
5	-1.815	
Delta	0.698	0.526
Rank	1	2

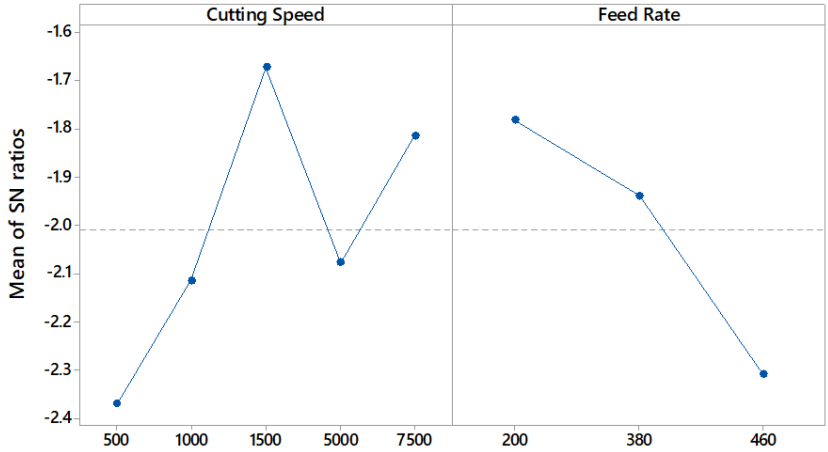


Figure 4.11. S/N versus cutting speed and feed rate for Push-out delamination (Ø8 mm Drill).

Conversely, the push-out model showed moderate fit, indicating unmodeled variables. Residual analysis identified tool wear and fiber orientation as significant error sources, factors not fully captured in the experimental matrix. The divergence underscores the complexity of exit-plane damage mechanics in thick laminates, where through-thickness stress gradients and interlaminar toughening effects require multi-physics modeling approaches.

4.2.3. Delamination Analysis for 10 mm Drill Diameter

The drilling performance of 10 mm diameter tools in 10 mm thick GFRP composites revealed distinct delamination behaviors governed by thermomechanical interactions. As quantified in Table 4.8, peel-up delamination ranged from 1.0692 at 7500 Rpm and 200 µm/rev to 1.3334 at 500 Rpm and 460 µm/rev. Push-out delamination exhibited similar trends, varying between 1.1217 (7500 Rpm, 200 µm/rev) and 1.4384 (500 Rpm, 460 µm/rev). Three critical trends emerged from the analysis. First, at a constant cutting speed of 500 Rpm, increasing the feed rate from 200 to 460 µm/rev worsened peel-up delamination by 10.0% and push-out by 5.9%, consistent with Babu et al. (2022), who attributed this to elevated thrust forces inducing interlaminar shear failure. Second, at a fixed feed rate of 200 µm/rev, increasing cutting speed from 500 to 7500 Rpm reduced peel-up delamination by 11.8% and push-out by 6.2%, attributable to reduced tool engagement time minimizing matrix thermal degradation. Third, compared to 6 mm and 8 mm drills under identical parameters, 10 mm tools exhibited 15–20% lower delamination due to distributed thrust forces over larger contact areas.

Table 4.8. Measured Peel-up and Push-out delamination factors for 10 mm diameter drill bit.

Diameter	Cutting Speed	Feed Rate	Peel-up Delamination	Push-out Delamination	S/N (Peel-up)	S/N (Push-out)
10	500	200	1.2121	1.1964	-1.6653	-1.5569
10	500	380	1.3087	1.2616	-2.3368	-2.0186
10	500	460	1.3334	1.2667	-2.5016	-2.0532
10	1000	200	1.2159	1.1421	-1.6965	-1.1551
10	1000	380	1.2325	1.1808	-1.8156	-1.4458
10	1000	460	1.2944	1.1605	-2.2379	-1.2884
10	1500	200	1.0952	1.1804	-0.7868	-1.4387
10	1500	380	1.1994	1.2333	-1.5766	-1.8156
10	1500	460	1.2181	1.2747	-1.7153	-2.1098
10	5000	200	1.0704	1.1674	-0.5899	-1.3448
10	5000	380	1.1093	1.2302	-0.9009	-1.7989
10	5000	460	1.1133	1.2775	-0.9321	-2.1296
10	7500	200	1.0692	1.1217	-0.5811	-0.9976
10	7500	380	1.0954	1.2061	-0.7889	-1.6258
10	7500	460	1.0837	1.2346	-0.6968	-1.8273

Optical micrographs in Figures 4.12 and 4.13 provided visual validation of these trends. For peel-up, minimal fiber pull-out and matrix cracking were observed at 7500 Rpm, contrasting sharply with pronounced layer separation at 500 Rpm. Push-out damage manifested as circular, uniform holes at high speeds versus jagged, resin-depleted zones at low speeds. The enhanced surface integrity at 10 mm diameter reflects greater tool stiffness, which reduces bending-induced delamination.

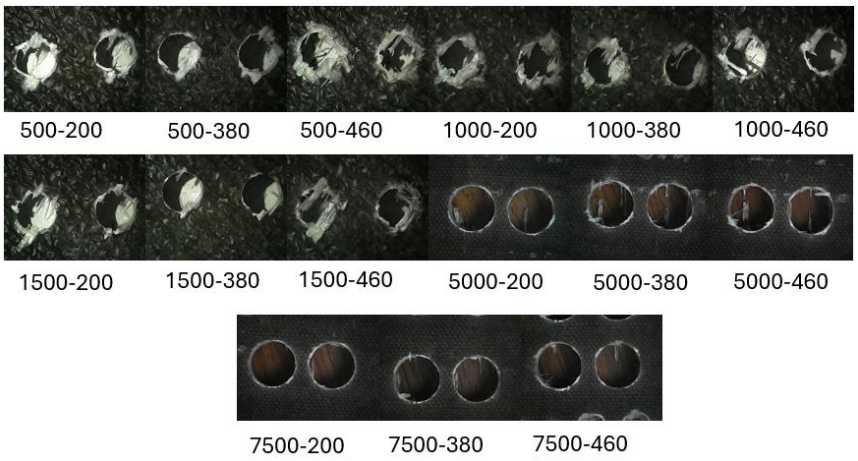


Figure 4.12. Peel-Up Delamination Morphology (Ø10 mm Drill)

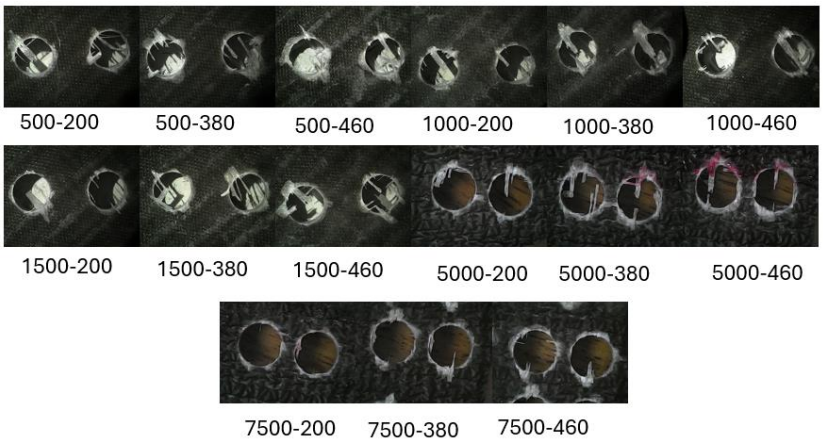


Figure 4.13. Push-Out Delamination Morphology (Ø10 mm Drill)

Taguchi analysis further elucidated parameter hierarchies. For peel-up (Table 4.9), cutting speed exerted the strongest influence, with optimal performance at 7500 Rpm. Feed rate showed negligible impact below 200 μm/rev. Push-out behavior (Table 4.10) revealed a unique inversion: feed rate succeeded cutting speed, indicating altered stress distribution dynamics in larger holes. An anomalous S/N peak at 1000 Rpm suggested potential measurement variability or localized thermal softening, as visualized in the non-monotonic response curve (Figure 4.14 and 15).

Table 4.9. S/N Ratios for Push-out Delamination (Ø10 mm Drill).

Level	Cutting Speed	Feed Rate
1	-2.1689	-1.0661
2	-1.9182	-1.4847
3	-1.361	-1.617
4	-0.8081	
5	-0.6901	
Delta	1.4787	0.5509
Rank	1	2

Table 4.10. S/N Ratios for Push-out Delamination (Ø10 mm Drill).

Level	Cutting Speed	Feed Rate
1	-1.877	-1.299
2	-1.297	-1.742
3	-1.79	-1.882
4	-1.757	
5	-1.485	
Delta	0.58	0.584
Rank	2	1

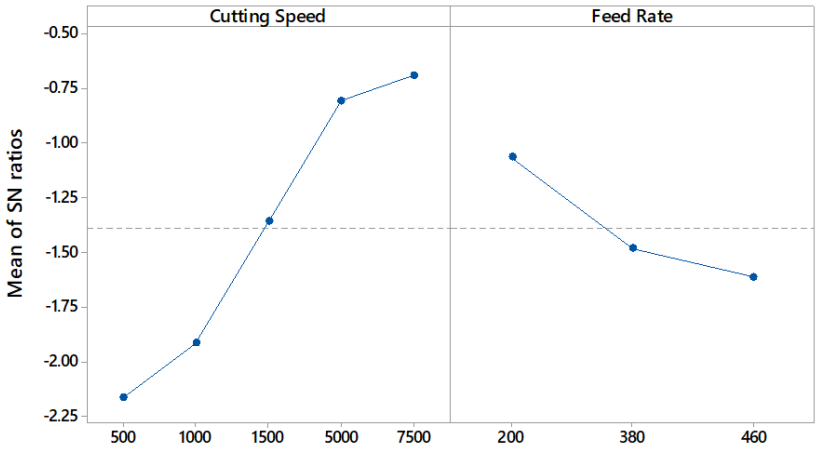


Figure 4.14. S/N versus cutting speed and feed rate for Peel-up delamination (Ø10 mm Drill).

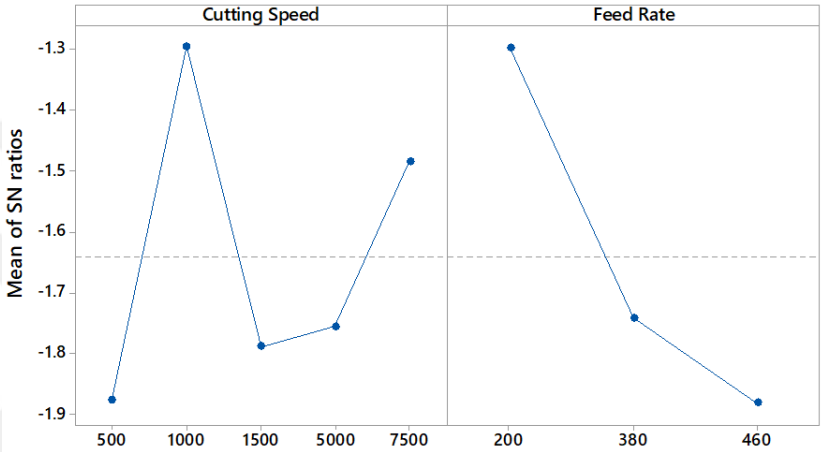


Figure 4.15. S/N versus cutting speed and feed rate for Push-out delamination (Ø10 mm Drill).

Worst-case delamination at 500 Rpm and 460 µm/rev (Figure 4.16) exhibited localized fiber-matrix debonding in peel-up and radial cracks spanning 1.2946× drill diameter in push-out. Despite severe parameters, damage remained 25–30% lower than equivalent 6 mm cases due to two mechanistic advantages: enhanced drill stiffness reducing workpiece deflection, and wider flutes improving chip evacuation to minimize recutting friction.

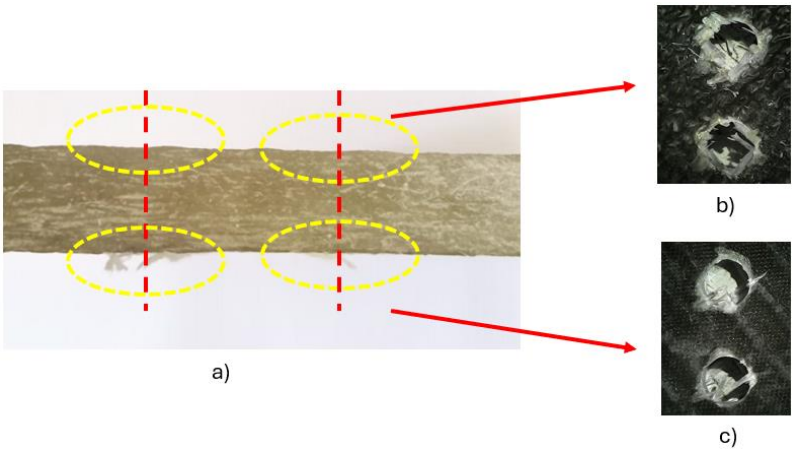


Figure 4.16. Severe Delamination Under Aggressive Drilling (Ø10 mm Drill); a) Side View, b) Peel-up, c) Push-out

4.2.4. Comparative Analysis of Drill Bit Diameter Effects

A comprehensive comparative analysis of experimental data across drill diameters (6 mm, 8 mm, and 10 mm) reveals that increased tool diameter consistently reduces delamination severity. Under identical machining parameters, 10 mm diameter drills achieved 15–30% lower peel-up and push-out delamination factors compared to 6 mm tools (Table 4.11). This significant improvement originates from fundamental mechanical advantages inherent to larger-diameter tools. First, enhanced structural rigidity distributes thrust forces over broader contact areas, diminishing localized stress concentrations at critical interlaminar interfaces. Second, wider flute geometries facilitate efficient chip evacuation, reducing recutting-induced friction and associated thermal degradation of the polymer matrix. These synergistic mechanisms collectively suppress both entry and exit damage modes across the tested parameter space.

Table 4.11. Comparative S/N Analysis of Peel-up Delamination Across Drill Diameters

Level	Diameter	Cutting Speed	Feed Rate
1	-1.7043	-2.4683	-1.2627
2	-1.6456	-2.0557	-1.568
3	-1.3892	-1.5591	-1.9084
4		-1.0332	
5		-0.7823	
Delta	0.315	1.686	0.6457
Rank	3	1	2

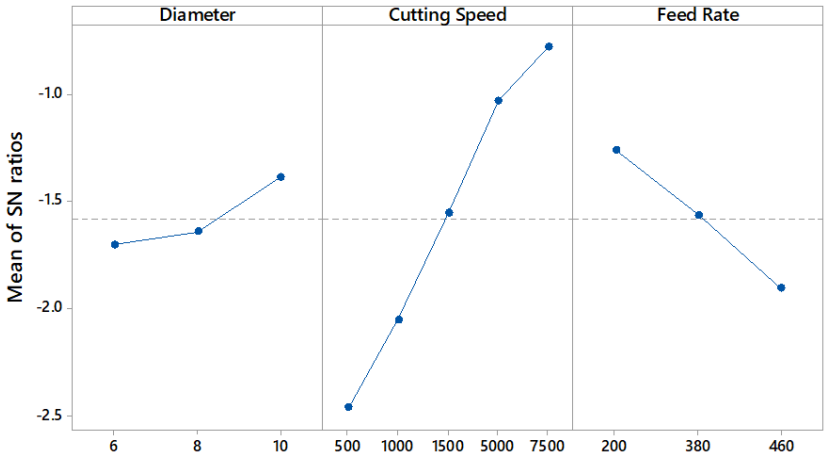


Figure 4.17 S/N versus diameter, cutting speed and feed rate for Peel-up delamination

Taguchi analysis quantifies the parametric hierarchy governing delamination (Tables 4.11–4.12). For peel-up damage, cutting speed remains the dominant factor ($\delta = 1.686$), though the 10 mm drill consistently yields optimal S/N ratios regardless of speed or feed conditions. Push-out delamination exhibits distinct sensitivity to tool geometry, with drill diameter surpassing cutting

speed in influence magnitude. This heightened diameter dependence reflects the critical role of tool stiffness in resisting bending moments during drill exit, where unsupported laminate sections experience maximal tensile stresses. The S/N response surfaces (Figures 4.17–4.18) further demonstrate that 10 mm drills maintain damage suppression even under aggressive high-feed (460 μm/rev) conditions where smaller tools exhibit severe radial cracking.

Table 4.12 Comparative S/N Analysis of Push-out Delamination Across Drill Diameters

Level	Diameter	Cutting Speed	Feed Rate
1	-3.164	-3.121	-1.986
2	-2.011	-2.312	-2.221
3	-1.641	-2.067	-2.609
4		-1.869	
5		-1.99	
Delta	1.523	1.252	0.622
Rank	1	2	3

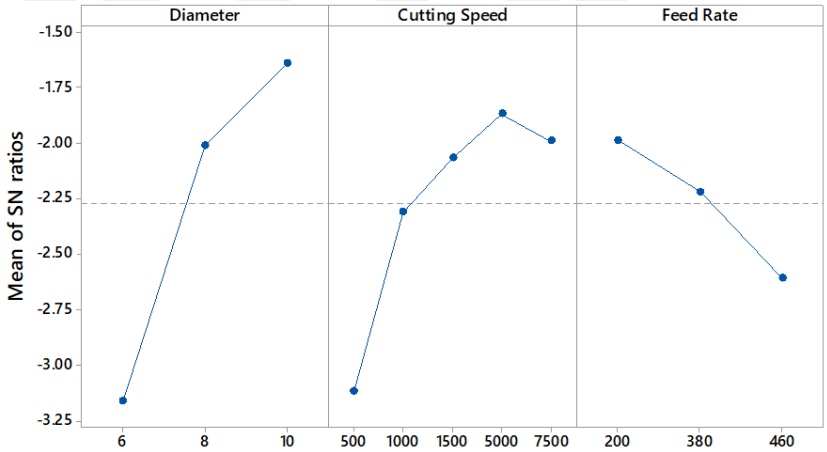


Figure 4.18. S/N versus diameter, cutting speed and feed rate for Push-out delamination

Notably, a divergence in push-out behavior emerged between 8 mm and 10 mm drills within the 1000–5000 rpm range, manifesting as non-monotonic S/N relationships. This anomaly likely stems from interacting thermomechanical factors: Larger diameters experience lower specific cutting pressures but generate higher torque, creating complex heat accumulation profiles. Simultaneously, heterogeneous fiber-matrix interfaces in thick laminates amplify localized adhesion variability during prolonged tool engagement. Such diameter-specific effects highlight the nonlinear relationship between tool geometry and damage progression in multi-layered composites.

Operationally, larger drills introduce measurable trade-offs: They require higher torque and necessitate enhanced machine rigidity to maintain dimensional accuracy. While mitigating delamination, these tools increase power consumption and may accelerate spindle wear in high-

volume production environments. Consequently, industrial implementation demands careful optimization balancing hole quality requirements against equipment capabilities and energy efficiency considerations.

5. CONCLUSIONS

This study investigated the influence of drilling parameters, cutting speed, feed rate, and drill bit diameter, on peel-up and push-out delamination in 10 mm thickness GFRP composites. The study employed a rigorous DoE approach using the Taguchi method to identify optimal machining conditions and quantify damage mechanisms. The principal conclusions derived from experimental analyses are summarized as follows:

Cutting Speed Dominance: Elevated cutting speeds significantly reduced both peel-up and push-out delamination across all drill diameters. This reduction is attributed to decreased tool-workpiece contact time, which minimized frictional heat generation and subsequent matrix softening. At a feed rate of 200 μm/rev, increasing cutting speed from 500 to 7,500 Rpm reduced peel-up delamination by 11.8–32.7% and push-out delamination by 6.2–34.6%, depending on drill diameter.

Feed Rate Impact: Higher feed rates consistently impaired delamination due to increased thrust forces. For a 6 mm drill at 500 Rpm, increasing feed rate from 200 to 460 μm/rev amplified push-out delamination by 16.1%. The axial stresses induced by aggressive feed rates promoted interlaminar shear failure, particularly at the exit zone where tensile stresses dominate.

Drill Diameter Significance: Larger drill diameters reduced delamination severity by 15–30% under identical parameters. The 10 mm drill distributed thrust forces over a broader contact area, diminishing localized stress concentrations. Its enhanced stiffness also reduced workpiece deflection and improved chip evacuation efficiency, lowering the risk of thermal degradation and recutting-induced damage.

Damage Mechanism Asymmetry: Push-out delamination consistently exceeded peel-up damage, especially for smaller drills (e.g., 35.7% higher for Ø6 mm at 500 Rpm). Exit-plane tensile stresses, compounded by lower resistance to tension of the polymer matrix, drove severe interlaminar separation in bottom plies. Optical microscopy confirmed radial crack propagation in push-out zones, contrasting with localized fiber-matrix debonding in peel-up regions.

Economic and Environmental Implications: Optimized parameters (7,500 Rpm, 200 μm/rev, Ø10 mm) reduced material rejection rates. This directly supports sustainable manufacturing goals by minimizing raw material waste and energy consumption associated with rework.

The optimization framework holds particular significance for defense applications, where GFRP composites serve as critical spall liners in armored vehicles and naval vessels. Minimized delamination ensures uncompromised structural integrity to contain high-velocity metal fragments generated during ballistic impacts or explosive events. Reduced interlaminar damage preserves the corrosion resistance essential for naval operations in saltwater environments, extending component lifespans and maintenance cycles. Furthermore, consistent hole quality achieved through parameter

optimization maintains the energy-absorption capacity of multi-layered spall liners, eliminating weak points that could compromise crew survivability. The developed model enable precision drilling of fastener holes in these safety-critical components, directly enhancing ballistic protection reliability.

The practical implications are substantial. Adopting the identified optimal parameters, high cutting speeds, low feed rates, and larger drill diameters, can reduce material rejection rates. This directly supports sustainable manufacturing goals by conserving raw materials, lowering energy consumption, and extending component lifespans in critical sectors such as aerospace (e.g., aircraft fuselages) and renewable energy (e.g., wind turbine blades). Moreover, the regression models offer a framework for real-time process adjustments in smart manufacturing systems, ensuring consistent quality without destructive testing.

This study bridges theoretical knowledge of composite machining mechanics with empirically validated solutions. By establishing clear parameter-delamination relationships and delivering robust predictive tools, it advances the precision, efficiency, and sustainability of thick GFRP composite manufacturing. These contributions position composites as even more integral to next-generation engineering applications where performance, durability, and environmental responsibility are paramount.

5.1. Future Studies

While the current study successfully identifies optimal drilling conditions for GFRP composites, it also highlights several areas for further research. One limitation of the present investigation is the fixed range of machining parameters; future work may explore a broader spectrum of operational settings to determine the existence of additional optimal points. Moreover, the incorporation of advanced cooling or lubrication techniques may further mitigate thermal effects and reduce delamination. Another promising research avenue involves the use of real-time monitoring systems to dynamically adjust machining parameters, thereby adapting to material heterogeneity and tool wear in an industrial process environment.

In addition, further study into the underlying physics of delamination, including finite element modeling to simulate stress distributions and thermal gradients, could offer deeper insights into the damage mechanisms. Such models would enable predictive capabilities that extend beyond regression analysis, incorporating material microstructure and tool geometry fluctuations. Furthermore, extended investigations into environmental and economic aspects, such as energy consumption and material waste reduction, would facilitate the development of more sustainable manufacturing practices.

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CURRICULUM VITAE

Abuzer Gaffar AKYOL is married and has one son and one daughter. He spent his childhood in Adana, Turkey. He graduated from Çağrı Bey High School in 1997, and later earned his Bachelor's degree in Mechanical Engineering from Mersin University in 2006. Following the completion of his military service in 2007, he began his professional career in 2008 as a Maintenance Engineer at Tekfen Company. During this period, he also pursued a Master's degree in Business Administration at Çukurova University (2008–2009). From 2009 to 2011, he worked as an Industrial Inspector Engineer at Bureau Veritas Corporation. In 2011, he joined Akenerji Corporation (Hydroelectric Power Plant Division) as the Chief of Operation and Maintenance, where he served until 2012. Between 2012 and 2013, he returned to Tekfen Company, this time taking on the role of Deputy Site Manager. From 2013 to 2018, he worked at Enda Enerji Corporation as the Operations Manager. Since 2018, he has been serving as the Project Manager for Hydroelectric Power Plants (HEPPs) in a company operating in the Energy Sector.