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Machining High-Pressure Laminate for Furniture Manufacturing: Cutting Forces, Surface Quality, and Business Strategy Implications

Mohamad Ridzuan Jamli[1*], Azrul Azwan Abdul Rahman[1], Al Emran Ismail[2]
[1]Faculty of Technology and Industrial Engineering and Manufacturing, Universiti, Teknikal Malaysia Melaka, Durian Tunggal, Melaka, Malaysia, [2]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
*Email: ridzuanjamli@utem.edu.my

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Abstract
High-Pressure Laminate (HPL) is increasingly important in the furniture industry because it is strong, comes in many styles, and is affordable for mass use. Over time, it has moved from just being used in homes to being adopted in schools, hospitals, offices, and hotels. Newer versions, such as antimicrobial HPL, are also opening up uses in healthcare and education. Still, machining this material is not straightforward. From what we noticed during machining, the layered resin structure tends to wear tools faster, causes higher cutting forces, and makes it harder to get smooth surfaces. Ideally, very high spindle speeds, more than 20,000 RPM, would be needed. Yet, in reality, many small and medium enterprises (SMEs) only run CNC machines with about 8,000–10,000 RPM. This shows a clear gap between what is recommended and what actually happens in workshops.In this work, we carried out trials to see how machining settings affect cutting forces and surface quality. At the same time, we tried to link the results to business points such as return on investment, the possibility to scale up production, and how companies can position themselves in the market. The results were not always the same in every trial, but in general, higher feed rates and larger stepovers made cutting forces higher and surfaces rougher. When the settings were kept moderate, the finish looked better, though the machining took longer. These trade-offs matter in practice, especially for SMEs that must think about cost, time, and quality at once. From this, the study offers some useful observations that both smaller shops and larger manufacturers could use as they plan to compete in the global furniture industry.
Keywords: High-Pressure Laminate (HPL), CNC Machining, Cutting Forces, Tool Wear, Surface Finish, Business and Manufacturing

Introduction

The furniture industry worldwide is changing at a fast pace. Customers want new designs, sustainability rules are getting stronger, and digital tools are spreading into production. In the middle of all this, High-Pressure Laminate (HPL) has become a key material. HPL is made by pressing together sheets of kraft paper that are soaked in phenolic resin, with a decorative top sheet, under heat and pressure. The process gives a material that is strong, durable, and flexible in design (Prestes Pires et al., 2019). To put it simply, it resists scratches, moisture, heat, and even impact. For many manufacturers, this balance of toughness and cost makes it a practical option. The demand is rising not only in furniture but also in interiors and construction. At the same time, digital technologies are changing how firms work. Wiedenbeck & Parsons (2010) observed that companies in furniture, cabinet making, and millwork are increasingly using digital systems for design, production, and supply chain tasks. The point here is that material choice and digital adoption are linked. HPL fits well in this shift because it offers both durability and flexibility while aligning with digital workflows. This shift matters for materials like HPL because companies now prefer products that not only look good and last long, but also fit well with computer-aided design and digital production methods. Recent innovations are also expanding HPL's role. Antimicrobial HPL, for instance, creates cleaner surfaces that are useful in healthcare, schools, and hospitality settings (Magina et al., 2016). This shows that HPL is not just a common material but can also serve niche, high-value markets where hygiene, durability, and safety are critical. Companies that can bring these new types of HPL into their product range stand a better chance to compete in markets that allow for higher pricing. Apart from machining, other production methods are being studied as well. Atwee et al. (2023) compared conventional machining with laser-based processes and found that new technologies can cut down on waste, reduce production time, and give more freedom in design. These methods are not yet widely used for HPL, but they may become either competitors or complements to CNC machining in the future.

However, the machining of HPL remains a persistent technical and economic challenge. The abrasive, resin-filled layered structure accelerates tool wear and increases cutting forces, leading to frequent tool changes and higher operating costs. Research has demonstrated that fiber-reinforced composites, including laminates, present machining bottlenecks that are fundamentally different from those encountered in metals (Gao et al., 2022). As Adamik et al. (2025) emphasized, both process factors and material variability jointly determine machining quality. Recognizing this interaction allows businesses to better align their technical strategies with market demands and long-term competitiveness. Delamination, small cavities, and rough surfaces problems show up a lot when machining isn't set right. It's not rare. In theory, the advice is simple: use high-speed spindles, maybe 20,000 to 24,000 RPM. At those speeds you usually get cleaner cuts, smoother finishes. But that's the theory. Reality looks different. Many smaller furniture shops are running CNC machines that top out around 8,000–10,000 RPM. Much slower. And that gap matters.So they face a choice. Push the machine harder make it cuts faster. But the tools wear out quickly, and the finish often goes bad. Hold back make the tools last longer, surfaces look better. But output drops. Again, the point is the machine itself sets the limits, not just the operator.. If they play it safe with slower settings, then the quality improves but cycle times increase. So, what looks like a technical adjustment quickly becomes a business matter,affecting cost control, market choices, and even how a company presents itself to customers. Surface finish is where this problem shows up most clearly. Wang et al. (2017) noted in work on composite laminate milling that things like cavity marks and fiber pull-out were strongly linked to cutting forces and fiber direction. These flaws may look small, but they have a big impact on whether a product is accepted or rejected. Furniture buyers, especially at the high end, check not only strength but also how the surface feels and looks. A piece with chipped edges or rough patches might be rejected outright, which limits a manufacturer to cheaper, lower-margin markets. For firms trying to move up to mid- or high-end segments, controlling machining quality is not optional, it is central to strategy. The same logic applies when it comes to choosing tools. Li et al. (2020) described how polycrystalline diamond (PCD) tools hold up far better than carbide under abrasive laminate machining. They keep their edge longer, which means fewer changes and more consistent quality. But the downside is the upfront price, which is often hard for SMEs to justify with tight budgets. Carbide tools, while much cheaper at first, need to be replaced again and again, which drives up operating costs over time. This leaves managers asking a familiar question: do they spend more at the start for PCD and save later, or keep using carbide and accept higher running costs? Either way, the decision is not just technical, it shapes profitability and growth in the longer term.

Surface roughness has increasingly become a central topic in machining research. For example, Song et al. (2022) developed a model for CFRP milling that included the effect of fiber distribution in order to predict surface finish during high-speed dry milling. Although HPL and CFRP are not the same material, both share a layered structure reinforced with fibers and resins, and this makes machining more complex than with solid plastics or metals. What their work shows is that predictive modeling can be used to estimate surface quality under certain cutting conditions. In other words, instead of waiting to see defects after machining, firms could use such models to plan ahead and adjust settings before problems appear. For small and medium enterprises, even a simplified model might provide a useful, low-cost tool for process improvements. Larger firms, by contrast, might combine advanced predictive systems directly into their Industry 4.0 platforms. Looking across the literature, however, a clear gap emerges. Many studies have looked in detail at cutting forces, surface roughness, or tool wear in laminate machining. At the same time, business studies have considered trends, markets, and competitiveness. But very few works link the two,technical outcomes on the shop floor and their direct influence on business strategy. As a result, managers often lack a framework for connecting machining choices with higher-level goals. This study tries to close that gap by bringing both sides together. Experimental trials were carried out on HPL milling under realistic spindle speed limits, and the results for cutting forces and surface quality were measured. These outcomes were then connected to questions of cost, scalability, and positioning in the market. The findings suggest that machining strategy is not simply a narrow engineering concern. Instead, it has a strong impact on return on investment (ROI), competitiveness, and long-term sustainability in the furniture industry.

Methodology

The methodology for this work was set up to carefully examine how High-Pressure Laminate (HPL) behaves during CNC milling. The focus was placed on two main responses, cutting forces and surface roughness, since these are directly connected to tool wear, stability of the process, and in the end, the cost-effectiveness of production in the furniture sector. A mixed approach was used. On the one hand, quantitative experiments provided measurable data. On the other hand, qualitative observations helped interpret the outcomes so they could be linked not only to engineering performance but also to possible business implications. The test material consisted of industrial-grade HPL sheets. These were made by compressing several layers of kraft paper saturated with thermosetting phenolic resin, with a decorative printed sheet on the surface. For consistency, each specimen was prepared to the same size: 100 × 152 mm, with a thickness of 12 mm. The average weight was about 350 g, and the density measured 1.92 g/cm³. These numbers match typical commercial specifications, so the machining results would represent real industrial practice rather than just lab-specific samples. Before running the trials, every piece was checked visually to make sure there were no defects such as delamination, uneven surfaces, or contamination. This step was important to reduce the chance of biased results caused by material inconsistencies. Figure 1 illustrates one of the prepared specimens mounted in position for testing

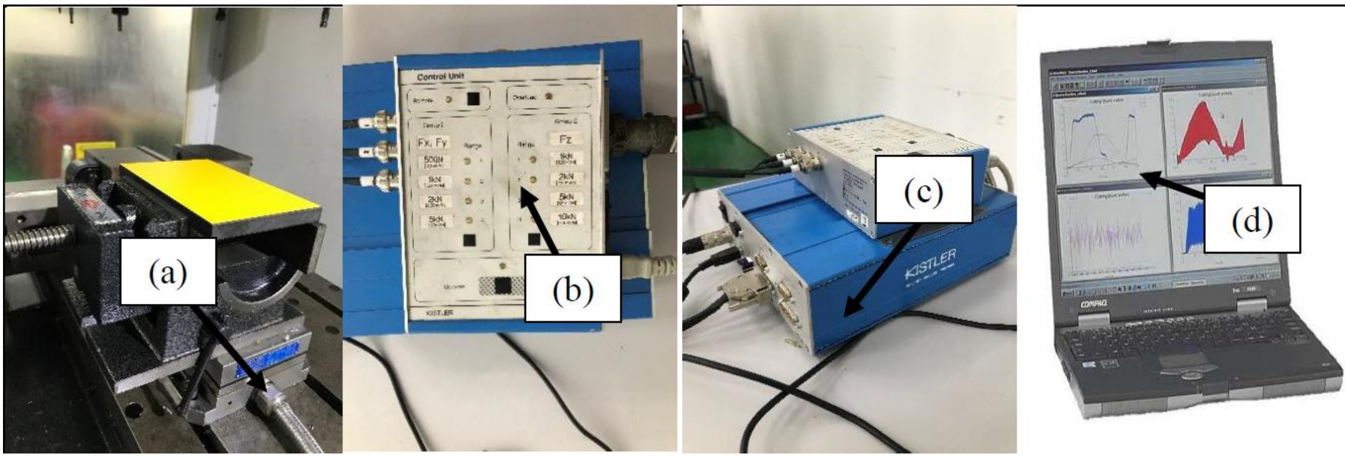

Figure 1: Dynamometer setup for cutting force measurement (a) Dynamometer of type 9257BA,(b) Control Unit 5233A1 ,(c) DAQ BOX 5697A1 and (d) Dynoware software.

All machining trials were conducted on a HAAS VF-1 three-axis CNC milling machine, equipped with a maximum spindle speed of 8,100 RPM, a power capacity of 22.4 kW, and torque up to 122 Nm at 2000 RPM. While this spindle speed falls below the recommended range for laminate machining (20,000–24,000 RPM), it is representative of the equipment typically available in small to medium-sized enterprises (SMEs). By replicating these constraints, the study ensured that its outcomes would remain directly relevant to the operational realities of firms with limited capital resources. Figure 2 illustrates the HAAS VF-1 used in this study.

Figure 2: HAAS VF-1 CNC milling machine used for HPL experiments

Cutting forces were measured using a Kistler 9257BA piezoelectric dynamometer, selected for its high sensitivity (5 pC/N) and ability to capture dynamic force fluctuations during milling. The dynamometer was connected to a Control Unit 5233A1 and a DAQ Box 5697A1, forming a robust data acquisition system. Signals were processed in Dynoware software, which enabled real-time recording of three orthogonal force components (Fx, Fy, Fz) at frequencies up to 5 kHz. Figure 3 illustrates the experimental force measurement setup.

Figure 3: Kistler 9257BA dynamometer connected to CNC setup.

The force signals were analyzed statistically to identify maximum resultant forces (Fr), representing the combined tool load during machining. These values were compared across different parameter settings to establish trends. Reznicek et al. (2023) emphasized the importance of decomposing resultant forces into directional components, as percentage ratios of forces reveal how different parameters redistribute cutting loads across axes. By incorporating this perspective, the study ensured a more holistic understanding of tool loading. Surface finish was evaluated using a Mitutoyo SJ-301 portable roughness tester, which provides direct Ra (arithmetic average roughness) readings in micrometers. Measurements were taken at three different locations along each machined edge, and mean values were calculated to ensure statistical reliability. The use of Ra as the primary metric followed established practices in laminate machining research, where Ra values serve as both engineering indicators of process stability and proxies for consumer perception of product quality (Song et al., 2022; Wang et al., 2017). Each HPL specimen was mounted on the CNC machine worktable, ensuring firm clamping to minimize vibration. The tool offsets were calibrated, and zero points were established to maintain consistency across all trials. Cutting passes were executed under varying feed rates, stepovers, and depths of cut. The dynamometer continuously recorded real-time cutting forces, while the surface roughness tester was used immediately after machining to capture Ra values along the milled edges.

After collecting the data, the results were first organized into spreadsheets and then analyzed with basic statistical tools. We calculated mean values, standard deviations, and correlation coefficients to see how different machining settings were related to the outputs. In interpreting the data, earlier studies were used as a guide. For instance, Gao et al. (2022) pointed out several machining bottlenecks in fiber-reinforced laminates, while Wang et al. (2017) showed how cutting parameters affect cavity defects and surface quality. These references provided context for what we were seeing in the HPL trials. In the final stage of analysis, machining parameters were correlated with the measured responses. Cutting force values (Fr) were compared directly with roughness values (Ra) to look at the trade-off between tool loading and surface finish. Outliers were taken out so that the patterns shown in the data would reflect actual machining behavior, not odd anomalies. Even after that, the correlations were not simple. Some were linear, others non-linear, which shows just how complex HPL machining really is. Song et al. (2022) reported a similar problem when they tried to predict surface roughness in fiber-reinforced composites. They found that the way fibers were distributed made it difficult to get accurate predictions. In other words, irregular structures in the material add layers of uncertainty. The instruments and parameters we chose were deliberate. SME-grade CNC machines were used on purpose because they reflect what many small and medium manufacturers actually have on the shop floor. The goal was not to create an ideal lab setup but to mirror real-world limits. Both cutting forces and surface roughness were measured because they give two sides of the same story. One side shows tool wear and productivity, the other shows finish quality and how products might be judged in the market. To make sure the analysis was not done in isolation, we grounded it in earlier studies. Work by Gao et al. (2022), Reznicek et al. (2023), Song et al. (2022), and Wang et al. (2017) provided a baseline for comparison. This way, the findings could be reproduced and also tied back into wider academic debates as well as the practical concerns of industry.

Results and Discussion

Cutting Force Behavior and Technical Insights

Looking at the cutting forces gives a clearer picture of how machining settings affect tool load when milling High-Pressure Laminate (HPL). The measurements were taken with a Kistler 9257BA dynamometer, and some clear patterns stood out. When feed rate went up, the forces climbed quickly as well. Under the more aggressive conditions, they often passed 200 N. In other words, pushing the settings harder meant much higher loads on the tool. At more moderate feed rates, the forces stayed under about 150 N and were steadier. The machining process was smoother, with fewer sudden spikes. Stepovers showed the same kind of trend. Larger stepovers engaged more material each time the tool passed, which raised the overall forces. Smaller stepovers spread the cutting more evenly. This kept the forces lower and more consistent from pass to pass. Again, the point here is that both feed rate and stepover directly shape how predictable or unstable the forces become. Smaller stepovers, however, spread the material removal more evenly and produced lower, steadier force levels. These observations are in line with Gao et al. (2022), who pointed out the machining difficulties linked with fiber-reinforced laminates. With HPL, the interaction between the tool edge, the resin-rich layers, and the fiber directions often makes the force patterns less predictable compared to cutting metals. Other researchers have reported similar behavior. For instance, Wang et al. (2017) found that sudden spikes in cutting force during CFRP milling were closely tied to cavity defects, showing how force fluctuations directly affect surface quality. Frydrýšek et al. (2022) also noted that cutting loads in HPL tend to vary in a more random or stochastic way. According to their study, this unpredictability complicates both the estimation of tool wear and the overall process optimization.

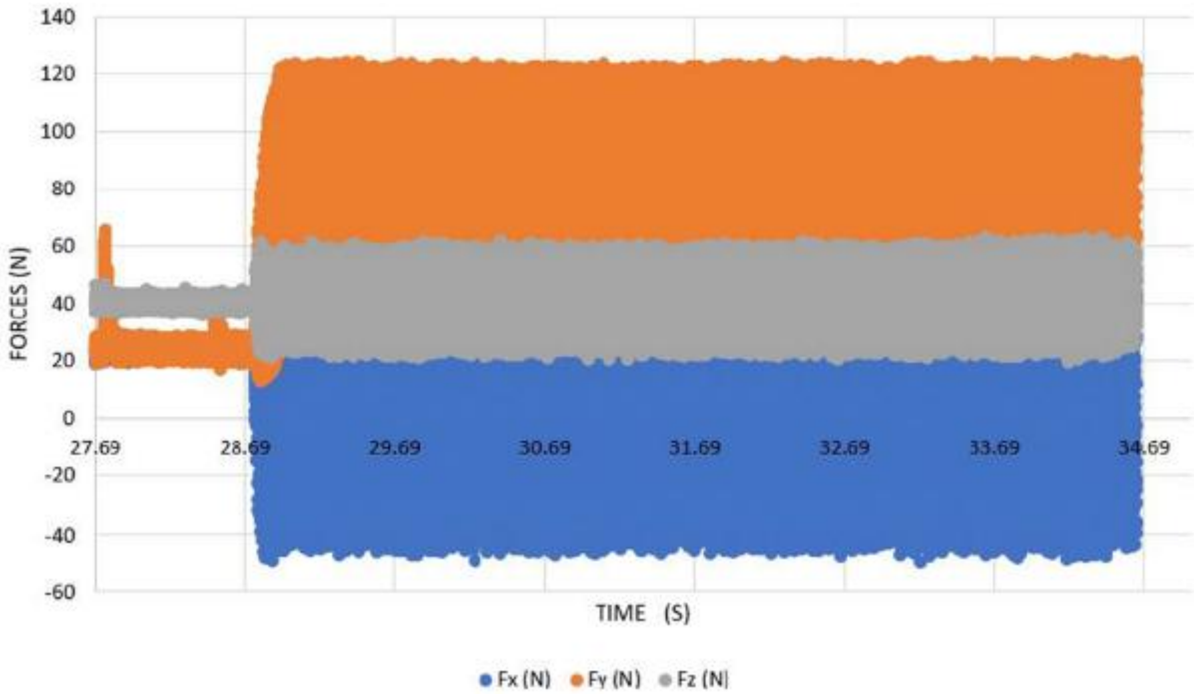

Figure 4: Measurement of the forces Fx, Fy and Fz vs Time

From a business perspective, cutting force behavior directly influences tooling costs, maintenance requirements, and production continuity. High cutting forces accelerate wear on carbide tools, requiring more frequent replacement. For instance, a workshop producing 500 panels per week under aggressive parameters may replace a carbide end mill after every 50 parts. At USD 60 per tool, this results in USD 600 per week in tooling expenses, or nearly USD 2,400 per month. In contrast, PCD tooling, although priced between USD 300–500 per tool, can withstand thousands of cuts when forces are controlled, spreading the investment over a longer lifecycle (Li et al., 2020). Excessive cutting forces also risk overloading machine spindles, leading to unplanned maintenance. Downtime in furniture manufacturing is particularly damaging because production is often tied to batch contracts with strict delivery schedules. Missed deadlines not only incur financial penalties but also harm client relationships and brand credibility. Thus, controlling cutting forces is not a purely technical goal but a strategic necessity for ensuring reliability and preserving customer trust.

Maximum Resultant Forces and Scalability Trade-Offs

The force data showed that stepovers had a much bigger effect than expected. When the tool was run at a 100% stepover, the forces jumped up sharply. At 50%, the forces were much lower and more stable, but the cycle time almost doubled. This is really the core trade-off for companies that want to increase production. Small firms, in particular, often feel pressure to push their machines harder to save time. But the downside is clear: higher forces mean faster tool wear, rougher finishes, and more stress on the machine itself. In the long run, these hidden costs can cancel out the short-term productivity gain. On the other hand, reducing the stepover keeps the cut smoother and the process more stable, but it slows down daily output. In other words, the shop can either save the tools or save the time, but not both. Wang et al. (2017) made a similar point in their study on laminates, where they found that force spikes were linked to cavity defects. Their work suggests that pushing parameters too far does not just wear tools,it also reduces the chance of producing acceptable parts. For large companies, this is less of a problem, since they can spread work across several machines. Smaller shops, with only one or two machines, face much tighter limits. The cost of tooling also plays into this. If a shop is running carbide tools aggressively, they may go through 10 tools in a week, at around USD 600. Add to that the downtime,about 10 minutes per change, or 100 minutes a week,and the hidden labor cost rises too. With PCD tools, the situation looks different. Even though each tool costs USD 400 upfront, one can last for around 1,000 parts. That means fewer tool changes, less downtime, and a lower cost per part overall. Li et al. (2020) pointed out that for abrasive laminates, PCD often pays back its higher initial price over the long term. Again, the decision here is not only about engineering. It is also about return on investment and the ability of a business to stay competitive.
The scalability problem can be summed up quite simply:

- High stepover / high feed rate: more throughput, but high cutting forces, tool wear, poor finish, and higher rejection rates.
- Moderate stepover / feed rate: better surface finish and longer tool life, but slower daily output.

For SMEs, this choice often defines their role in the market. If they choose productivity, they risk being locked into low-margin, price-driven markets. If they choose stability and quality, they may serve fewer customers, but with higher loyalty and less price pressure. Larger firms can escape this trade-off by investing in high-speed spindles and PCD tooling. Routers operating at 20,000–24,000 RPM allow both faster removal and smoother finishes. Gao et al. (2022) argued that such equipment upgrades are among the most effective ways to overcome machining bottlenecks. But for many SMEs, the capital cost remains a big barrier. In the end, what this shows is that cutting forces are not just numbers on a graph. They directly shape tool life, production capacity, and even market strategy. Managing these forces becomes a way to manage the business itself. Smaller firms must balance carefully within their limits, while larger firms can use better equipment to expand with fewer compromises.

Surface Roughness Trends

Surface roughness analysis revealed clear patterns in response to feed rate and stepover. At moderate machining settings (feed rates of 200 mm/min, stepovers of 50%), average Ra values were between 0.67 and 0.80 µm, as shown in Figure 5. These finishes are consistent with acceptable standards in mid-range furniture production, where edges must be smooth to the touch and visually clean. However, at higher feed rates and 100% stepovers, Ra exceeded 1.0 µm, producing visible chipping and edge defects. The relationship between resultant cutting forces and surface roughness is shown in Figure 3. Although there was a general trend of higher forces correlating with rougher surfaces, several anomalies were observed. In some cases, elevated forces coincided with acceptable surface quality, suggesting that additional variables,such as tool wear, material inconsistencies, or vibration dynamics,also played roles. Horava et al. (2024) further demonstrated that tool design factors, particularly the number of inserts used in face milling, significantly influenced roughness outcomes. Their findings reinforce the conclusion that surface quality in laminate machining cannot be explained by process parameters alone but must account for tool configuration effects.

These results reinforce prior work by Wang et al. (2017), who showed that in CFRP milling, cavity defects and fiber pull-out were strongly linked to localized force spikes. Similarly, Song et al. (2022) emphasized that predictive roughness models must incorporate not only parameter settings but also microstructural features of laminates, such as fiber distribution and resin interaction. For HPL, this suggests that deterministic parameter-based rules may not fully capture surface outcomes; instead, probabilistic or data-driven models may be more appropriate. In business terms, surface roughness has a direct bearing on customer perception, brand reputation, and market positioning. In premium furniture markets, buyers expect smooth finishes free of visible defects. A panel with chipped edges may be deemed unacceptable, even if structurally sound. For SMEs producing 500 panels weekly, a 10% rejection rate due to poor surface finish translates to 50 unusable panels, or USD 1,000 in weekly losses (assuming a material cost of USD 20 per panel). Over a month, such losses exceed USD 4,000, a significant hit for smaller workshops. Conversely, companies that invest in machining strategies to consistently achieve smoother surfaces can command higher prices in mid-to-high-end segments. These markets are less price-sensitive and reward superior quality with brand loyalty. The additional cycle time required to achieve Ra values under 0.8 µm may reduce output, but the premium pricing offsets productivity losses, yielding stronger profit margins. This dynamic underscores the strategic role of machining in shaping not only production efficiency but also brand differentiation.

Gao et al. (2022)observed that firms able to overcome machining bottlenecks in laminates gain competitive advantages in markets where aesthetics and performance converge. The divergence in surface outcomes translates directly into market segmentation strategies. Firms that prioritize throughput over finish quality often accept higher roughness values (Ra > 1.0 µm), enabling them to compete in low-margin, volume-driven markets such as budget furniture, institutional fittings, or mass-produced components where function outweighs aesthetics. These markets are highly competitive, with thin margins and limited customer loyalty. Firms that can keep their surface finishes smooth, Ra values under 0.8 µm, tend to be in a stronger place. It gives them access to mid- and high-end markets. That means premium furniture, office fittings, or even hotel interiors. In these areas, customers look closely at the details. Brand reputation and finish quality matter a lot. The look of the product and the way it feels in the hand often decide whether a buyer will pay more or commit to a longer contract. In other words, appearance carries as much weight as strength. Sometimes even more. Again, the point is simple. Machining outcomes are not just technical results. A smoother finish becomes part of the business strategy, it shapes how the company is seen and where it can compete. There are also openings in more specialized niches. Antimicrobial HPL, for example, has been studied by Magina et al. (2016) and is especially attractive for hospitals, schools, and hotels, where hygiene and durability are priorities. For these types of customers, machining strategies that give a consistent, clean finish are not just helpful but necessary. Without that, entry into such markets becomes very difficult. Again, the point is that machining outcomes are not only technical results. They feed directly into strategy. To put it simply, the quality of the finish becomes a business lever, it helps firms stand out, build reputation, and shape their position in the market.

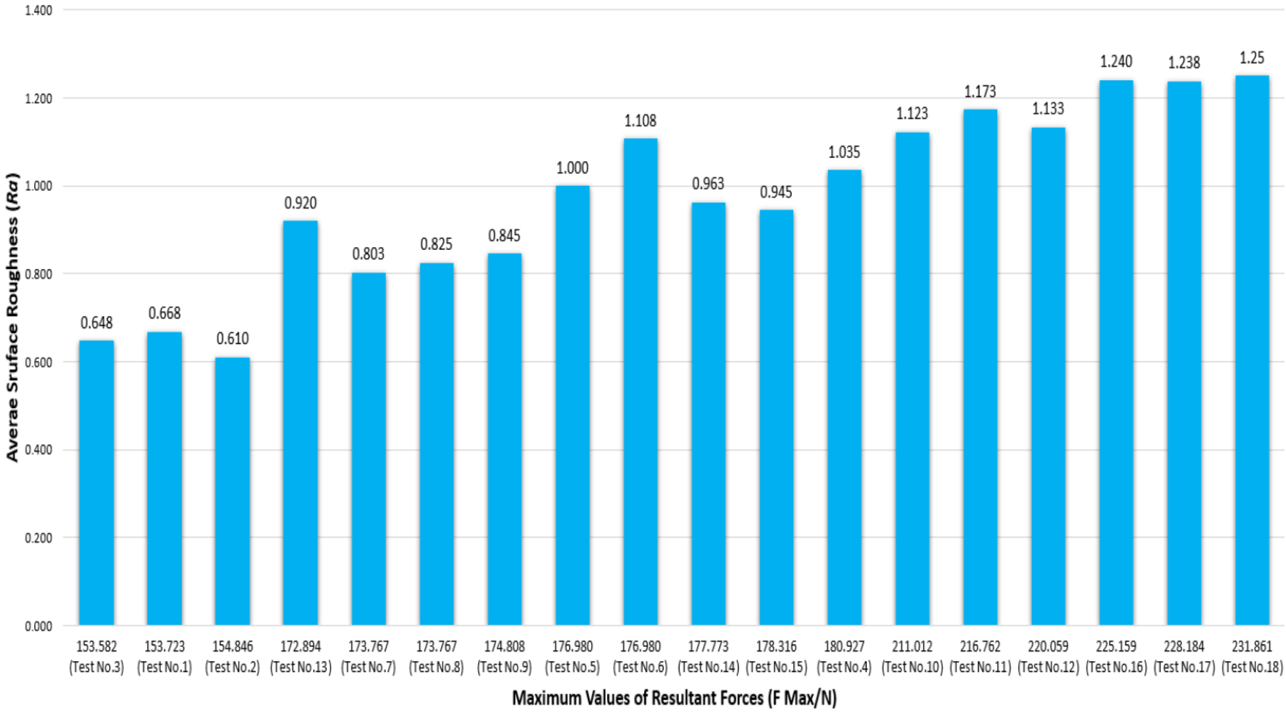

Figure 5: Correlation of Ra and F Max/N

The findings show a sharp contrast between small firms and large companies when it comes to machining challenges. For SMEs, the limits are obvious. Their CNC machines usually run at 8,000 to 10,000 RPM, and that was the case here too. This means they are working under strict speed limits. They cannot simply add capacity by changing settings, because the machines themselves set the boundary. What they can do is adjust within those limits. They try to balance feed rate, stepover, and depth of cut to get a finish that customers will accept, while also keeping tool wear under control. It's a careful balancing act, and it works only up to a point. The downside is that these compromises hold them back. Many SMEs reach a ceiling in output and cannot scale further. The point here is not that they fail to survive. Most can stay active in local or regional markets. The real problem is moving up. Competing in export markets or premium contracts requires both high volume and high quality at once. And with spindle speeds capped where they are, SMEs struggle to deliver both. Again, this makes it difficult for them to break out of lower-margin segments. Larger companies face a completely different reality. Because they have more resources, they can buy high-speed CNC routers that run between 20,000 and 24,000 RPM. These machines remove the spindle speed bottleneck. What this means is that they can achieve faster material removal rates while still producing smoother finishes. Yang et al. (2020) also observed that when cutting forces are too high, tool wear speeds up and cutting temperatures rise, adding thermal stresses to both the machine and the workpiece. With high-speed spindles, the forces and heat stay lower, which explains why bigger firms usually report more stable processes and more consistent product quality.

Investment in tooling adds another layer. PCD tools, as highlighted by Li et al. (2020), last much longer and resist wear better than carbide. While they cost more at the start, larger firms can justify the purchase because they save on tool changes and downtime in the long run. The return on investment makes sense for them. SMEs, however, often cannot afford the upfront cost, so they continue with carbide and accept higher running expenses. What this really shows is that the same technical data, force levels, surface finish, tool wear, leads to very different strategies depending on firm size. SMEs end up focusing on small optimizations and carving out niches, while large firms use their resources to buy capacity and scale into market leaders.

In short, machining HPL is not just a technical exercise but also a strategic question. Surface quality, spindle speed, and tool wear affect not only productivity but also brand reputation, market access, and profitability. SMEs and larger companies face different realities: one group works within limits, the other invests to remove those limits. To put it another way, machining cannot be separated from business planning. Firms that connect their machining choices to ROI, customer needs, and positioning in the market will have a better chance to grow. Those that do not risk being stuck in commodity segments with low margins.

Conclusion

This work looked at how High-Pressure Laminate (HPL) behaves when machined, focusing mainly on cutting forces, surface finish, and what these results mean for furniture manufacturers. The experiments showed very clearly that feed rate and stepover matter a lot. When the settings were pushed too high, the cutting forces shot up,often past 200 N,and the surface became noticeably rougher, with Ra values above 1.0 µm. Under those conditions, tools wore out quickly, spindles took more stress, and the chance of parts being rejected increased. At more moderate settings, the surface finish improved (around 0.7 µm Ra) and the cutting action was smoother. The price paid was longer machining times and slower output. So the trade-off is straightforward but important: speed versus quality. In practice, this is not just a machining choice,it shapes business strategy. A company chasing aggressive settings might see short-term productivity gains, but it also pays in extra tool costs, more rework, and higher rejection rates. In the end, this usually keeps them in lower-margin, high-volume markets. Firms that slow down and aim for cleaner finishes, even if machining takes longer, can sell into premium furniture markets where design and consistency allow higher prices and stronger loyalty. Tooling makes the picture even clearer. Carbide is cheaper and easy to replace, but wears out fast. Polycrystalline diamond (PCD), although expensive upfront, lasts much longer and reduces downtime, meaning the total cost per part is lower across the tool’s life. To put it simply, tooling choice is not just about engineering, it changes the economics.

The differences between small and large firms also came out strongly. SMEs, most of them stuck with spindles below 10,000 RPM, have to make the best of what they already own. Larger firms can spend on 20,000–24,000 RPM routers and PCD tooling, which lets them produce more and maintain surface quality at the same time. Going forward, it will be important not only to run technical tests but also to link them with wider issues. Adding cost modeling, consumer perception studies, and sustainability checks into machining research would help make sure that technical improvements line up with profitability and long-term growth in the global market.

This study adds to machining research in a few practical and theoretical ways. From the theoretical side, it tries to close a gap that often exists between engineering performance and business reality. Many earlier works talk about cutting forces, surface roughness, or tool wear, but they usually stop there. What this study does differently is connect those results with what actually happens in a company, how technical choices affect cost, productivity, and market position. In simple terms, it treats machining not just as an engineering activity but as part of business strategy. Contextually, the focus here is on small and medium-sized firms that use the kind of machines most researchers overlook. These are machines with spindle speeds of only 8,000 to 10,000 RPM, much slower than the high-end routers often used in academic work. By grounding the tests in this reality, the study reflects how most furniture makers actually operate day to day. This makes the findings more useful for firms that have to find a middle ground between quality, tool wear, and production speed. Overall, what this research shows is that machining High-Pressure Laminate (HPL) cannot be separated from the business environment around it. The results help extend current knowledge by showing how process parameters connect with economic outcomes. In other words, machining performance and business strategy share the same space, and understanding both is key to sustainable growth in modern furniture manufacturing.

Future Research

Future studies on High-Pressure Laminate (HPL) machining need to do more than just test parameters one by one. The next step is to connect them with business outcomes. That means building techno-economic models where feed rate, stepover, or tool choice can be directly linked to cost per part, ROI, and profitability. To put it simply, changing a number in the workshop should be shown in the numbers on the balance sheet. For small and medium firms, this kind of tool could be the difference between guessing and making clear investment choices. Tooling is another area that deserves attention. Right now, shops mostly choose between carbide, which is cheap but wears fast, and PCD, which is durable but expensive at the start. But there are possible in-between solutions. Options like coated carbides or diamond-like coatings could fill that gap. What’s needed is proper testing, side by side, under the same conditions. And not just on one type of machine, comparisons should cover both the entry-level SME CNCs and the faster routers used by bigger firms. Only then can we see what the real strategic advantage of upgrading might be. (Zhuang et al., 2023) reminded us that cutting force stability is one of the most important challenges in machining research. Fluctuating forces shorten tool life and reduce process stability. Applying that idea to HPL could give manufacturers steadier results and lower running costs. Finally, there is the customer and environmental side. Studies on how people actually judge surface quality, combined with sustainability assessments, would help ensure technical improvements match what the market values and what regulations are starting to demand. Again, the point here is that machining research cannot stop at the technical level, it must show how engineering choices tie into profitability, customer expectations, and long-term responsibility.

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