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Improving Slot Milling Performance Using Ultrasonic Vibration Assistance

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ABSTRACT

This study aims to improve the machinability of materials, focusing on carbon steel A36, through the application of Ultrasonic Vibration-Assisted Machining (UVAM). Traditional machining methods face significant challenges when dealing with such materials, including high cutting forces, poor surface finish, and rapid tool wear. UVAM addresses these issues by introducing controlled high-frequency vibrations (26 kHz) to the workpiece during the cutting process, enhancing the overall machinability.

The research compares UVAM to Conventional Milling (CM) under various cutting conditions, analyzing key machinability parameters such as cutting forces, surface roughness. By applying vibrations to the workpiece, UVAM reduces the tool-workpiece contact time, resulting in improved chip formation and more efficient debris evacuation. This study demonstrates that UVAM reduces cutting forces by up to 40% and surface roughness by up to 54% compared to CM. These results highlight UVAM's effectiveness as a machining technique, particularly for hard-to-cut materials. The significant improvements in surface finish and cutting forces indicate that UVAM can be a valuable solution for industries requiring high-precision machining and enhanced tool performance.

Keywords: Ultrasonic Vibration-assisted machining (VAM), Milling, Axial vibration, Surface roughness, Cutting force.

1 INTRODUCTION

The rising demand for high-precision components in industries such as aerospace, automotive, and electronics has led to the development of advanced manufacturing technologies. The ultrasonic vibration frequency commonly used in vibration-assisted machining processes is typically more than 20 kHz [1]. Ultrasonic Vibration-Assisted Machining (UVAM) represents a major advancement in this area, addressing limitations of traditional machining methods by improving precision, efficiency, and product quality. Many attempts to use ultrasonic vibration-assistance technology in different manufacturing processes has been reported in machining, forming and joining [2]–[4]. In machining processes, UVAM enhances traditional machining by incorporating controlled vibrations, which optimize chip formation, reduce cutting forces, and improve material removal rates, surface finish, and tool life. This makes UVAM a key technology in precision engineering, surpassing the capabilities of conventional methods [5]. UVAM uses dynamic cutting by introducing controlled vibrations between the tool and workpiece, optimizing machining. This reduces cutting forces, improves chip removal, increases material removal rates, enhances surface finish, and extends tool life. By leveraging vibrations, UVAM exceeds the limits of conventional machining, boosting both productivity and precision [2],[6]. Since the 1970s, UVAM has proven highly effective for materials resistant to conventional methods. By introducing microscopic vibrations, UVAM shifts cutting from continuous grinding to rapid tapping, significantly reducing cutting forces and improving surface finish, as confirmed by numerous studies [7].

UVAM is widely used in industries like aerospace, automotive, medical, and mold manufacturing. In aerospace, it helps machine complex parts like turbine blades and engine components [7]. Automotive manufacturers use UVAM to boost productivity and quality in engine blocks and transmission parts. In the medical field, UVAM enables precise production of implants, prosthetics, and devices. The mold industry benefits from faster, more accurate machining for plastic injection molds [8]. UVAM is categorized by the direction of applied vibration: longitudinal and lateral. In longitudinal vibration, vibrations are parallel to the cutting direction, improving chip fragmentation, evacuation, and reducing cutting forces, which enhances surface finish [9]. Lateral (or transverse) vibration applies perpendicular oscillations, inducing tool chatter that aids chip segmentation and control, also reducing cutting forces and improving surface finish [10]. UVAM can also be classified by how vibrations are introduced: tool-based, workpiece-based, and hybrid. In tool-based vibration, piezoelectric actuators or magneto-strictive materials impart vibrations to the cutting tool, offering flexibility for tool replacement without altering the setup [9]. Workpiece-based vibration uses vibrating platforms or fixtures to apply vibrations to the workpiece, ideal for large or complex parts [11]. Hybrid vibration combines both methods, maximizing chip control, surface finish, and reducing cutting forces [12].

UVAM enhances machining by applying mechanical vibrations to the cutting tool or workpiece, either superimposed on the primary motion or separately. This versatile technique improves performance across various machining processes, making it ideal for precision manufacturing. In turning process, Ultrasonic Vibration-Assisted Turning (UVAT) enhances conventional turning by introducing controlled vibrations, improving surface finish, reducing cutting forces, and increasing material removal rates [13]. UVAT's origins date back to the 1940s with the first use of ultrasonic vibrations in metal cutting. Over time, various methods like piezoelectric and magnetic actuators have been developed, making UVAT a valuable tool in industries such as aerospace, automotive, and precision engineering. Ongoing research continues to advance UVAT, positioning it for broader applications in the future of precision machining [12,14,15]. In milling process, Ultrasonic Vibration-Assisted Milling (UVAM) is an advanced machining technique that integrates high-frequency vibrations into conventional milling to improve material removal rates, surface finish, and tool life [16]. By superimposing vibrations on the cutting tool, UVAM disrupts continuous cutting, forming smaller chips, reducing cutting forces, and enhancing heat dissipation [17]. This leads to faster machining times and greater productivity. UVAM also improves surface quality by minimizing built-up edges and reducing tool wear, resulting in smoother, higher-quality finishes ideal for precision applications in industries like aerospace, automotive, and medical [7]. Additionally, UVAM extends tool life by preventing excessive wear, leading to longer service intervals and reduced maintenance costs, especially when machining difficult materials or performing complex operations [18]. As an innovative combination of traditional milling and vibration technology, UVAM offers substantial benefits over standard methods and is expected to play an increasingly significant role in modern manufacturing as research continues to advance [19].

In drilling process, Ultrasonic Vibration-Assisted Drilling (UVAD) enhances drilling efficiency, especially in difficult materials and deep holes, by incorporating controlled axial vibrations. These vibrations improve chip breaking, reduce cutting forces, and facilitate chip evacuation [15]. Originating from early vibration-assisted machining techniques, UVAD was first explored in the 1960s, initially focusing on brittle materials before expanding to conventional metals and alloys [20]. UVAD offers several advantages over traditional drilling, such as better chip control, reduced cutting forces, improved hole quality, and higher material removal rates. The vibrations help break chips into smaller pieces, reducing tool wear and improving hole roundness, surface finish, and dimensional accuracy [21]. As research advances, UVAD is expected to play a growing role in modern manufacturing, offering a valuable solution for improving drilling performance across various industries. In grinding process, Ultrasonic Vibration-Assisted Grinding (UVAG) is an advanced technique that combines traditional grinding with controlled mechanical vibrations, significantly improving performance. By introducing high-frequency oscillations to the grinding wheel or workpiece, UVAG reduces grinding forces, minimizes wheel wear, and enhances surface quality [22]. First explored in the mid-20th century through ultrasonic machining, UVAG gained traction in the 1970s and 1980s due to the limitations of ultrasonic methods in metal applications [20]. UVAG offers several advantages, such as reduced forces, improved material removal rates, and minimized wheel loading, particularly in hard-to-machine materials like ceramics, composites, and hardened steels [8]. Widely used in aerospace, automotive, and precision engineering, UVAG enhances grinding efficiency and surface quality, making it essential for machining hard and brittle materials. As research progresses, UVAG is poised to play an even greater role in precision manufacturing [20].

Conventional milling (CM) uses a rotating cutter to remove material from a workpiece, but it can struggle with hard or brittle materials. UVAM addresses these limitations by introducing high-frequency vibrations to the tool or workpiece, disrupting continuous contact and offering several key benefits [7]. One major advantage is the reduction in cutting forces, as the vibrations create intermittent tool-material contact, which decreases tool wear and extends tool life, improving efficiency and lowering costs [23]. UVAM also enhances surface finish by breaking up chips more effectively, resulting in smoother surfaces and fewer burrs critical for applications requiring precision and aesthetics [15]. Additionally, UVAM boosts machining efficiency by allowing for higher feed rates and deeper cuts without sacrificing quality, reducing cycle times and manufacturing costs. Its versatility across a wide range of materials, including difficult-to-machine ones, makes UVAM a valuable tool in various industries [24]. Overall, UVAM offers reduced cutting forces, better surface finish, increased efficiency, and greater versatility, positioning it as a promising advancement for modern manufacturing. Previous studies have extensively compared UVAM with CM for various materials and applications. Liu et al. demonstrated that UVAM enhanced chip evacuation and shear slip, producing smaller chip curl angles [25]. Zhang et al. noted that UVAM produced consistent micro-texture but higher surface roughness and plastic deformation in titanium alloys compared to CM [14]. Several studies also explored UVAM's benefits in diverse applications. Bayat and Amini showed UVAM reduced distortion and milling force in aluminium alloys, improving flatness tolerance [24]. Ali and El-Hofy found UVAM enhanced surface finish in 7075 aluminium alloy [21]. Baraya et al. developed and calibrated a vibratory system for slotting, achieving reduced cutting forces, improved surface roughness, and minimized slot width error compared to CM [2], [26].

This research explores the control of machining and vibration parameters and their effect on milling performance, focusing on developing a one-dimensional ultrasonically vibratory device using a piezoelectric transducer to enhance UVAM. The device's effectiveness will be evaluated through its application in milling processes and subsequent workpiece characterization. The study's tasks include constructing the vibratory device, developing control mechanisms for the piezoelectric actuator, setting up the experimental system, determining cutting conditions, and conducting preliminary tests to refine them. Performance will be assessed by analyzing surface quality, cutting forces, of the workpiece characteristics, Finally, conclusions and recommendations will be formulated.

2 METHODOLOGY AND EXPERIMENTAL WORK

The utilized equipment during the experimental investigation is introduced in this section. This includes the machined workpiece, the CNC machine utilized, the components of the vibration generation system, and the monitoring system of the cutting forces. Moreover, machined surface characterization instruments are introduced. The procedure of conducting the experimental work in this investigation is presented as well.

2.1. Material:

Carbon Steel A36 was selected as the workpiece material, with dimensions of 30 mm x 25 mm x 13 mm. Its chemical composition and mechanical properties are shown in Tables 1 and 2 [27][28]. A36 is a widely used, versatile steel known for its strength, ductility, and weldability. Its cost-effectiveness and reliability make it ideal for construction and engineering applications, such as structural components (beams, columns, frameworks) in buildings, bridges, and towers. It is also used in the production of metal products like plates, pipes, and structural shapes for machinery, and in automotive components due to its high tensile and yield strength, which suit load-bearing applications. A36 can be easily formed, bent, and welded, enhancing its versatility, and is relatively inexpensive compared to other steel alloys, making it a popular choice in various industries

Table 1. Chemical Composition of Carbon Steel A36

Chemical Composition of Carbon Steel A36.					
Element	Fe	C	Mn	P	S
Wt.%	98.87	0.28	0.8	0.03	0.02

Table 2. Mechanical properties of Carbon Steel A36 [27,28]

Density kg/m3	7850
Elastic modulus GPa	200
Poisson ratio	0.3
Tensile strength MPa	500
Yield strength MPa	250
Thermal conductivity W/(m·K)	52
Hardness HV	170

2.2. Experimental Setup:

The experiments were conducted on the vertical machining centre (Victor – Vcenter-105) as shown in Figure1, capable of achieving spindle rotation speeds up to 6000 rpm. The machine features a table size of 1400 mm x 550 mm.

Figure 1: Victor – Vcenter-105 Machining Centre

2.2.1 Ultrasonic Vibration Setup:

To implement UVAM, an ultrasonic wave generating system in a single linear direction (1D) of 1 kW power and frequency of 26 kHz were connected to the vibration set. When activated, the device introduced ultrasonic vibrations into the machining process. When switched off, the system operated under CM conditions.

2.2.2 Machining and Equipment Setup:

All necessary components, including the workpieces and vibration generating system, were assembled on the milling machine's table, as shown in Figure 2. The experiments were performed using slot milling with a milling length of 5 mm, utilizing a (S260) 4 mm diameter carbide endmill with four flutes from Dormer Inc.

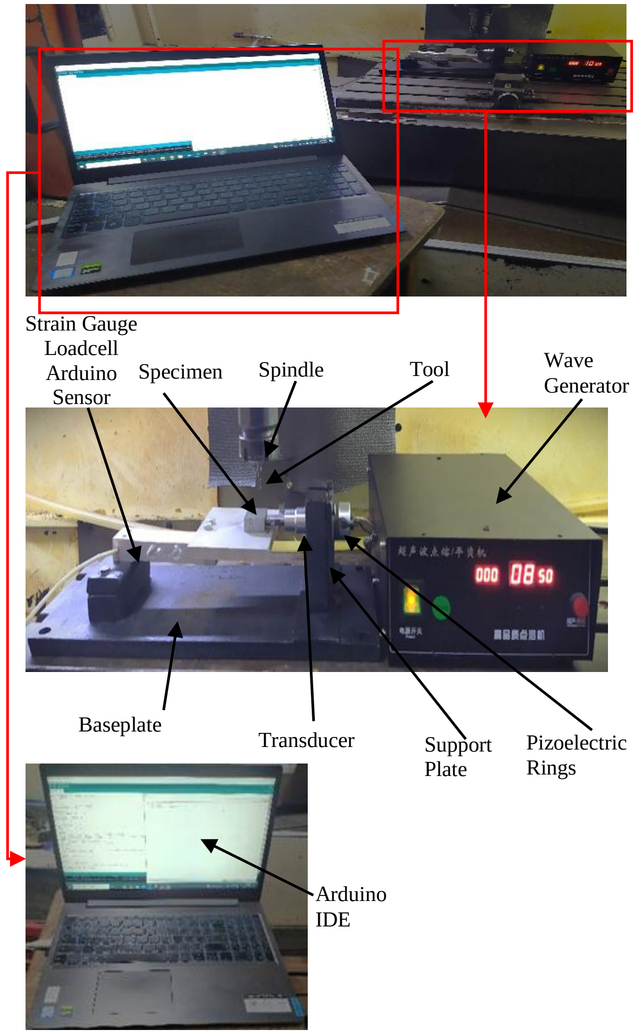

Figure 2: UVAM experimental setup

2.2.3 Measurement of Cutting Forces:

A load cell, connected to an Arduino card, was used to measure and record the cutting forces throughout the machining process. The connections between the load cell and Arduino are illustrated in Figure 3.

2.2.4 Surface Roughness Measurement:

After machining, surface quality was assessed using the TR200 Surface Roughness Tester (Figure 4). The TR200 is portable, easy to use, and provides accurate surface roughness measurements, making it ideal for industrial quality control.

2.2.5 Experimental Parameters:

According to the literature review, the specific parameter ranges used for the experiments are outlined in Table 3.

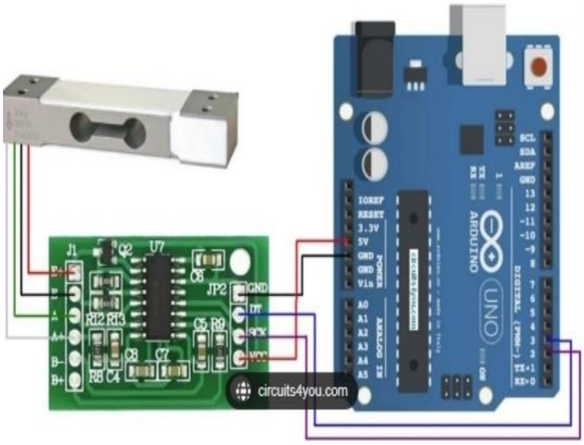

Figure 3: Loadcell Connections Diagram

Figure 4: Surface Roughness Tester TR200

Table 3. Overview of Experimental parameters

Level	Parameter				
	Vibration		Machining		
	Frequency (KHz)	Amplitude (µm)	DOC (mm)	Feed (mm/min)	Speed (rpm)
1	26	6 - 12	0.05	5	1000
2	26	6 - 12	0.1	10	3000
3	26	6 - 12	0.2	20	6000
4	26	6 - 12	0.3	30	

3. RESULTS AND ANALYSES

3.1. DOC impact on cutting force and roughness

To evaluate experimental efficiency and analyze the effect of depth of cut (DOC) on cutting force in both CM and UVAM, tests were conducted with a rotational speed of 6000 rpm, a feed rate of 10 mm/min, and varying DOC at 0.05, 0.1, 0.2, and 0.3 mm. The cutting forces for both UVAM and CM were measured independently. Figure 5 shows that cutting force is highly sensitive to changes in DOC. UVAM reduced cutting force by 25% to 40% compared to CM due to the interrupted cutting mechanism [16]. However, as the depth of cut increased, the pulsation effect of UVAM diminished due to the increase in cutting contact area, resulting in a higher average cutting forces [2].

Surface finish quality also improved significantly with UVAM. This observation attributed to the large size of the resulting chips in CM which damaged the surface roughness. By contrast, small chip size in UVSM due to the interrupted cutting mechanism, which leads to the ease of carrying away the resulting chips. Moreover, plastic deformation of the machined surface occurred in UVSM due to the complex tool tip waveform trajectory improves the machined surface roughness [29]. The average surface roughness (Ra) showed an improvement of 36% to 46% over CM, while maximum surface roughness (Rz) improved by up to 54%, as shown in Figures 6,7.

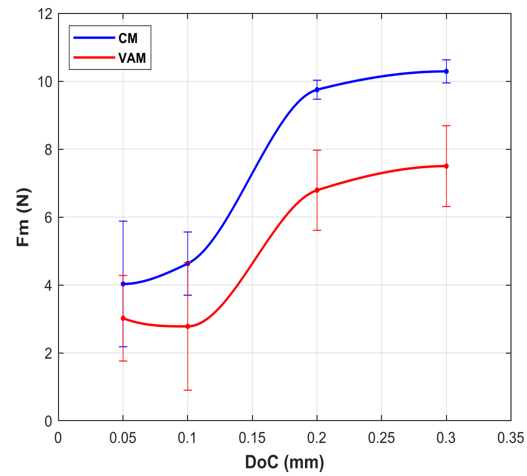

Figure 5: DOC impact on cutting force

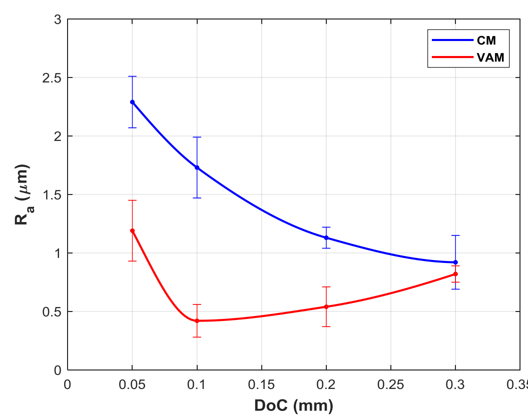

Figure 6: DOC impact on average surface roughness

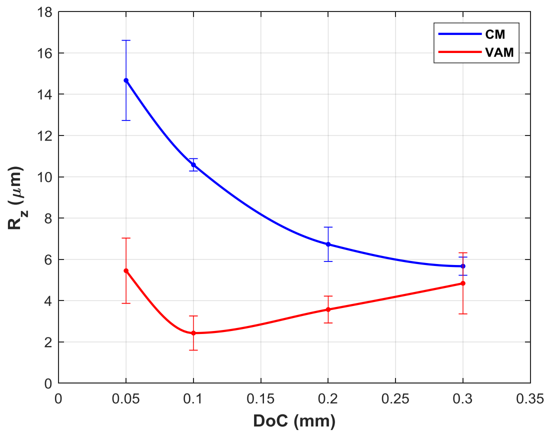

Figure 7: DOC impact on maximum surface roughness

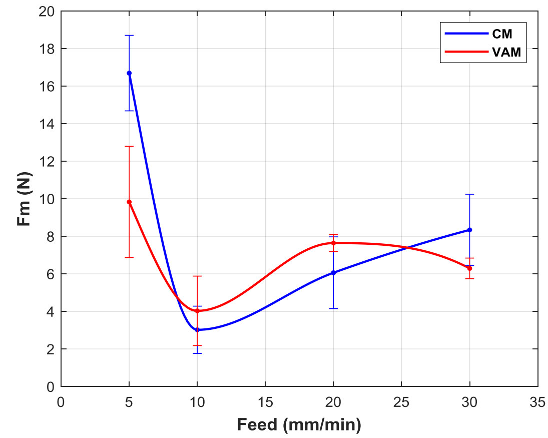

Figure 8: Feed rate impact on cutting force

3.2. Feed rate impact on cutting force and roughness

To investigate the impact of feed rate on UVAM cutting forces, experiments were conducted at a rotational speed of 6000 rpm and a DOC of 0.05 mm, with varying feed rates of 5, 10, 20, and 30 mm/min. Figure 8 compares the cutting forces in CM and UVAM across these feed rates. The analysis reveals that both UVAM and CM forces increase as the feed rate rises. However, the UVAM force grows at a faster rate than the CM force. This is likely due to the increased feed resistance, which reduces the amplitude of the vibrations, resulting in a higher total cutting force. Additionally, at very low cutting feed, the friction time between the tool and the workpiece is high leading to higher cutting forces. This can interpret the observation of higher cutting forces at 5 mm/min then it decreased before rising again [8,28].

Surface finish analysis showed that UVAM led to a 36% reduction in average surface roughness (Ra) compared to CM, with maximum surface roughness (Rz) improving by 48% as shown in Figures 9,10. A higher cutting feed reduces the machining time and the friction time between the tool and the workpiece, which leads to better surface quality. Moreover, introducing the UVSM in the experiments reduces more and more the contact time between the tool and the workpiece which produces much better surface roughness. Thus, at low cutting feed where the surface roughness values are high, applying UVSM has a considerable effect over the surface roughness when compared to the application of CM [24][31].

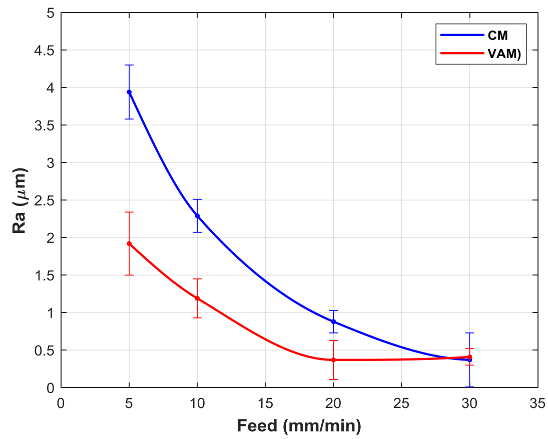

Figure 9: Feed rate impact on average surface roughness

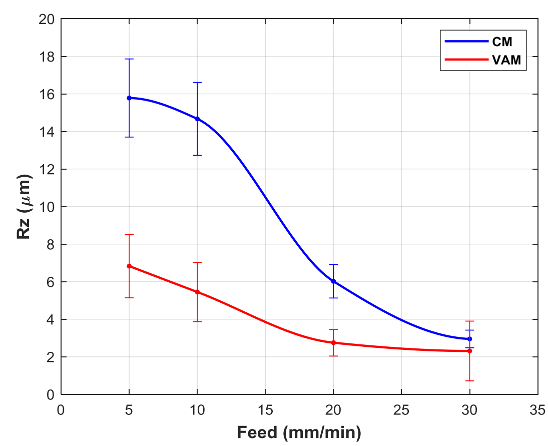

Figure 10: Feed rate impact on maximum surface roughness

3.3. Cutting speed impact on cutting force and roughness

To ensure experimental efficiency, a feed rate of 10 mm/min and a depth of cut DOC of 0.05 mm were used with varying cutting speeds of 1000, 3000, and 6000 rpm. Cutting forces for both UVAM and CM were independently measured. The low rotational speed increases the cutting forces because the tool-workpiece interaction process increases. The increase in the rotational speed leads to an increase in the cutting velocity, which causes a higher shear rate and heat generation. Thus, the shear strength of the material is reduced due to the thermal softening resulting from the generated heat in the shear zone [11]. Figure 11 shows the impact of cutting speed on cutting forces.

In terms of surface finish, Figures 12 ,13 represent the effect of changing the cutting speed on the surface roughness when applying UVSM and CM. The high rotational speed reduces the tool-workpiece interaction and applying UVSM provides more reduction of the contact time between the tool and the workpiece. This effect is observed in cutting speed results, where the surface roughness values are low at high rotational speeds and are lower when applying vibrations to the process.

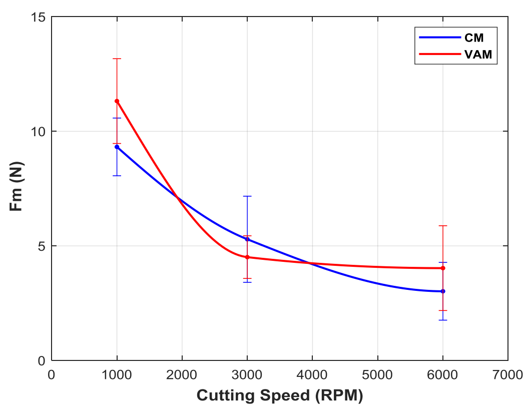

Figure 11: Cutting speed impact on cutting force

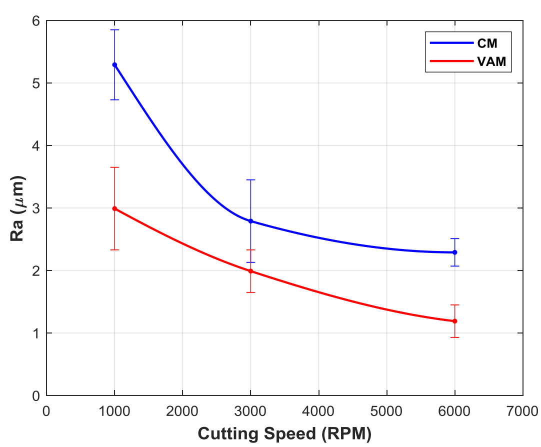

Figure 12: Cutting speed impact on average surface roughness

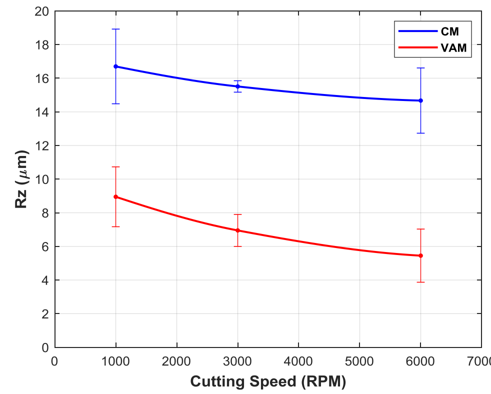

Figure 13: Cutting speed impact on maximum surface roughness

4. CONCLUSION

This paper focused on studying and applying UVAM processes, which have transformed the manufacturing industry by integrating controlled vibrations into CM processes. UVAM overcomes many limitations of CM, offering several key advantages:

- UVAM reduced cutting forces by 25% to 40% compared to CM. However, as the depth of cut increased, this reduction diminished, leading to a rise in the average cutting force.
- UVAM reduced cutting forces by 18% to 25% compared to CM. As cutting speed increased, UVAM's effectiveness decreased, and it transitioned to CM at a critical speed.
- UVAM improved average surface roughness (Ra) by up to 46% and maximum surface roughness (Rz) by up to 54% compared to CM in some experiments.
- The best results for machining Carbon Steel A36 were achieved with a vibration frequency of 26 kHz, amplitude of 8 μm, DOC = 0.1 mm, feed rate (f) = 10 mm/min, and cutting speed (n) = 6000 rpm.

Credit Authorship Contribution Statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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