An insight into ultrasonic vibration assisted conventional manufacturing processes: A comprehensive review

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Graphical abstract

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Abstract
Conventional manufacturing processes such as casting, forming, welding, machining, etc., have been optimized using different improvement techniques in the last few decades. The alterations in these processes have led to more efficient and productive manufacturing practices for the industry. One of these modification techniques is the deployment of ultrasonic vibrations in conventional manufacturing processes. In the last few decades, ultrasonic vibration assistance to manufacturing processes has seen an uprise and was the point of attraction for different research groups. Several improvements by utilizing ultrasonic vibration in manufacturing practices have been reported by the authors in the past. In this article, an attempt has been made to review all the reported techniques for different conventional processes viz. casting, forming, machining, and welding. The article outlines different research findings from the extensive work on ultrasonic vibration assistance showcasing the improved mechanical and morphological properties. The improvisation in the performance parameters viz. friction reduction, stress reduction, tool wear, surface finish, and grain structure has been witnessed by ultrasonic assistance in contrast to simple manufacturing processes. The outcomes have been summarized along with the optimized set of parameters from various studies.

Keywords
Ultrasonic vibration, casting, machining, mechanical, morphological, conventional manufacturing

Date received: 1 April 2022; accepted: 20 May 2022

Handling Editor: Chenhui Liang

Highlights
- A comprehensive review on ultrasonic assisted manufacturing processes.
- The effect of various input parameters of ultrasonic vibration setup is reviewed.
- Comparison with conventional processes have been reported.
- Outcomes of the various ultrasonic assisted hybrid processes have been summarized.

Introduction to VAM
Vibration-assisted manufacturing is one of the new techniques of manufacturing that is growing and finding many applications because of promising results. Vibration-assisted manufacturing processes, in general, have been performed using ultrasonic vibration. Ultrasonic vibrations are waves that propagate above the frequency of 20 kHz and these waves are beyond the human hearing range. These waves can propagate through different mediums and objects depending on the density of those mediums. The crystal lattice of metal when vibrated at a particular frequency can exhibit local motion of lattice points leading to randomness in the system. This randomness of the system is responsible for the characteristic changes in the properties of the solid object. The different characteristics of waves that can affect the object’s properties are frequency, amplitude, and wavelength.

The frequency and amplitude of ultrasonic vibration must be passed with a suitable arrangement to the object so that required changes can be made in the object. For a long time, the effect of ultrasonic vibrations has been studied for different manufacturing processes and observations have been reported. Ultrasonic vibration being a high-frequency vibration can improve the system stability without adding harmful vibrations to the system. The ultrasonic vibration can be transferred to the solid as well as liquid phase of material by using a suitable ultrasonic vibration setup.

Different research groups have applied ultrasonic vibration to different conventional manufacturing processes. Some of the important conventional processes such as machining, casting, forming, welding, laser cladding, direct laser deposition, etc. when combined with ultrasonic vibration can yield improved results. Ultrasonic vibrations can be transferred through different mediums such as solid as well as liquid phases and thus the ultrasonic-assisted manufacturing processes can be categorized into different types depending on the medium of travel. Figure 1 shows the classification of ultrasonic vibration having dependence on the medium of travel.

Different manufacturing processes
Manufacturing processes can be categorized into different types depending on the type of operation performed over the material. Some of the manufacturing processes are listed below
Different research groups have combined manufacturing processes with ultrasonic vibration and have reported positive as well as negative effects of ultrasonic vibration on material’s mechanical, thermal, rheological, and morphological properties.

**Vibration assisted casting**

Casting is one of the important manufacturing techniques where one can cast different complicated shapes of a product. The technology is used widely where one needs to cast complex shapes, intricate shapes, and desired shapes of different materials. In this technique, liquid metal is poured into the mold of intricate shape and the poured liquid material is allowed to settle at room temperature. The casting method is being used where complicated shapes cannot be manufactured by any other method or are uneconomical to produce using different techniques. Casting can also be used to produce batch-type production thus reducing the cost of manufacturing. Casting can be categorized into different types depending such as centrifugal casting, die casting, investment casting, lost wax casting, rapid casting, sand casting, etc. Figure 2 shows the different types of casting methods available for product manufacturing. These processes may also be combined with different other methods for better output. Different research groups have combined the casting technique with ultrasonic vibration setup and have reported the various effects of vibration on casting.

Different research groups have worked with ultrasonic vibration assistance in the casting process. Ultrasonic assisted casting has shown promising results in case of alteration of material matrix properties. Researchers have used ultrasonic vibration for reinforcement of silicon carbide (SiC) particles in the material matrix of aluminum alloy and it was observed that the particles of SiC were dispersed uniformly. With the increase of ultrasonic frequency, the grain size was not affected but morphological properties were seen to be changed significantly. The mechanical properties such as yield strength were observed to be improved with high ultrasonic vibrations by using 380–480 W of power source. The addition of 1 wt% of graphene in the material matrix of AZ31 Mg alloy has shown a positive response in mechanical as well as morphological properties. Researchers have highlighted that with 1 wt% of graphene nano elastic strength as well as...
nano hardness has been improved. It has also been observed the addition of more than 1 wt% of graphene had a negative impact on the corrosion resistance of the alloy.32

It has been observed that ultrasonic-assisted squeeze casting has positively impacted the properties of 2024 Aluminum alloy (Al). With the increase in the ultrasonic power up to 1.8 kW microstructures of the alloy were observed to be restructured into fine grains that lead to improved mechanical and morphological properties of the alloy. The study has reported a 20%–22% improvement in young’s modulus and ultimate tensile strength. Ultrasonic vibrations have resulted in the refinement of grains which is one of the important characteristics of alloy which decides the mechanical properties.33 Figure 3 shows the grain refinement with the increase in the ultrasonic vibrator power.33

Researchers have improved the mechanical properties of casted alloy by using ultrasonic-assisted vibrations while stirring the reinforcements of nanoparticles of SiC in AZ91 alloy. Different studies have observed the impact of stirring time on the grain size. The stirring time of 5 min has resulted in finer grain structure and smooth dispersion of nanoparticles along the grain boundaries of alloy. With the increase in the stirring time from 0 to 10 min, it has been observed that yield strength was improved from 60 to 110 MPa. Similar results were observed for the ultimate strength of alloy with increasing stirring time.34 Figure 4 shows the effect of ultrasonic vibration on the mechanical properties of SiC reinforced AZ91 alloy34 and the effect of stir timing while the stir casting process. Reinforcement of SiC particles in the alloy may also be done using the vortex method as well as the ultra-sonification method in stir casting. The two techniques have been analyzed and compared for 1 wt% SiC addition in the alloy. It was observed that ultrasonic vibration assistance to stir casting has a greater effect on the mechanical and morphological properties of alloy in comparison to the vortex method of reinforcement.35 Figure 5 shows the comparative results of the ultrasonic-assisted stir casting process with the double stir casting process.35 Similar results were observed when the ultrasonic-assisted stir casting technique was compared to the conventional stir casting process.36 Micro-size reinforcement of SiC particles in the alloy matrix of aluminum from 3 to 8 wt% has shown improvement in mechanical properties of alloy by using both techniques but ultrasonic-assisted techniques have shown greater impact than the other techniques.36

Zinc-based casting has shown poor mechanical properties due to the high brittleness of the metal matrix after solidification. The problem had been solved by the ultrasonic-assisted stir casting method by reinforcing silver (Ag), iron (Fe), and magnesium (Mg) in the alloy. The alloy composite with ultrasonic assistance had resulted in significant improvement in ultimate tensile strength from 33.6 to 361.88 MPa. The lost foam compound casting (LFCC) technique has been also combined with ultrasonic vibration assistance for uniform dispersions of Mg in the metal matrix of Al to refine the mechanical properties of metal matrix composite (MMC). It has been reported that ultrasonic assistance has improved the dispersion of Mg/Si in the material matrix of Al. The researchers have observed an 86.5% improvement in the shear strength of the bimetal alloy (Mg/Al) matrix when working with ultrasonic assistance.38

Reinforcement of 2 wt% nano SiC in the Al matrix had been reported by giving ultrasonic assistance to the squeeze casting process. The applied pressure in squeeze casting and ultrasonic vibration assistance in combination has led to the refinement of Al particles in MMC. The refined grain of MMC has shown better mechanical properties than normal casted alloy. Squeeze casting pressure of 400 MPa and ultrasonic assistance for 3 min combined have reduced the α-Al grains from 15.3 to 6 μm.39 Micro SiC particle reinforcement of 3% by volume in AZ91 alloy by using ultrasonic vibration-assisted stir casting process had shown significant improvement ultimate tensile strength of MMC while minor changes had been seen for elongation to fracture.40

The microstructural properties of MMC plays important role in the application of MMC. The mechanical, as well as microstructural properties, may be improved by adding suitable micro as well as nanoparticles in the MMC. For improvement, microstructural properties of graphene nanoparticles (GNP)
up to 0.9 wt% have been added to MMC by ultrasonic vibration assistance for a particular interval of time. The modified process has resulted in a 30%–40% increase in mechanical properties. The observed value of mechanical properties of GNP/Al MMC was 256.8 and 210.6 MPa for tensile and yield strength respectively. Many studies have been reported on hexagonal boron nitride (hBN) particle reinforcement in AA7150 Al MMC. The results have shown that the increase in the loading content of hBN up to 1.5 wt% has improved the ultimate tensile and wear properties.
of MMC but a higher reinforcement ratio led to a decrease in the MMC performance due to bigger agglomerations around the grain boundaries. The results have also shown improvement in the hardness of MMC with the refinement of alloy grains.

It has been observed that ultrasonic vibration time for stirring the liquid pool of metal as well as volume % or wt% reinforcement in MMC has a vital role to play in deciding the characteristics properties of final MMC. Further boron carbide (B₄C) and Hexa-boron nitride (hBN) in Al MMC have been reinforced in the hybrid matrix and the MMC has shown a 67% increment in mechanical properties. The results have highlighted that maximum 6 wt% reinforcement of B₄C in the Al base matrix has improved the tensile as well as the surface hardness of MMC. The 4 wt% of B₄C and 2 wt% of h-BN have shown the best result among other reinforcement levels of different hybrid composites.

Research studies have highlighted the impact of ultrasound on the mixing of B₄C and K₂TiF₆ in the molten pool of the Al matrix. It had been observed that when ultrasonic vibration was given to melt pool of composite for 5 min, the vibrations had helped in forming TiB₂ layer on B₄C layers which ultimately hinders the decomposition of B₄C layer. The smooth and uniform distribution of B₄C in the Al matrix leads to improvement in mechanical characteristics of composite.

Al₂O₃ nanoparticles when reinforced in Al matrix from 1.5 to 4 wt% have shown significant improvement in the tensile strength of material up to 3.5 wt% reinforcement level above 3.5 wt% has shown poor results due to the high agglomeration of nanoparticles at boundary grains. The maximum tensile (254.72 MPa) strength and hardness (74.25 HRB) of the sample were observed for 3.5 wt% of Al₂O₃ nanoparticles in the Al matrix.

Stir casting a conventional technique of casting was combined with ultrasonic assistance to study the various effects on mechanical properties and grain refinement characteristics of Al A356 alloy. From the study, it had been reported that ultrasonic assistance had improved the mechanical and morphological characteristics significantly.

The research literature also shows the improved tribological behavior of alloy when the nanoparticles of SiC up to 1.5 wt% in the Al-Mg-Si MMC were reinforced with ultrasonic vibration assistance. It had been noted that when speed, normal load, and distance were increased as the input to the pin on disk setup the wear rate was increased significantly. Whereas the nano SiC particle reinforced MMC had shown better wear properties compared to the monolithic Al alloy cast.

One of the studies reported the use of high-energy ball milling (HBM) for crushing the SiC particle up to 1.5–2 mm and the particle obtained through HBM were melted with Al matrix-assisted with ultrasonic vibrations. The study reported that 1 wt% reinforcement of SiC particles in the Al matrix leads to a 19% increase in mechanical performance, especially tensile strength.

The nanosized SiC particle reinforcement in the Al-5Cu matrix was done using ultrasonic assistance and time was varied for observance of the effect on the mechanical properties. It was noted that with increasing time of ultrasonic assistance up to 5 min the mechanical properties were improved due to better dispersion of SiC nanoparticles in the alloy MMC.

Based on the above literature different technologies such as stir casting, die casting process, and mold casting has been modified for ultrasonic vibration assistance. Figure 6(a) to (c) show the different schematics of the casting process which have been combined with ultrasonic vibration setup.

From the literature survey, it has been observed that many studies reported the use of ultrasonic vibration in the casting process but hitherto little has been reported on a novel setup of casting which combines the sand-casting technique with ultrasonic assistance. Hence in the future researchers can work on assisting the sand-casting process with ultrasonic vibrations to study the effect of ultrasonic vibrations on the sand as well as on the cast properties.

**Vibration assistance forming**

Forming or metal forming is a set of processes that converts the raw material into desired product shape or design by applying stresses, strain shear force, etc. Forging, wire drawing, extrusion, rolling, pressing, upsetting, thread rolling, etc. are some of the different forming operations. Research studies have shown that the forming process can also be combined with the ultrasonic vibration setup and the characteristics properties of the alloy can be altered to the required level.

Al 6063 alloy material, when processed for upsetting with ultrasonic assistance has shown improvement in mechanical behavior. It had been also observed that with ultrasonic assistance the upsetting load got decreased along with the material flow stress. The friction component between the workpiece and the die was decreased when compared to the conventional upsetting process.

Conventional forming for the incremental radial part had been improved by assisting the process with ultrasonic vibrations. The vibrations had reduced the internal stress generated due to forming process thus giving better control for the accuracy of geometric models.

The micro-forming process with ultrasonic vibrations has been studied and reported that under the compression forming process the amplitude to specimen height was one of the important aspects of the
The vibration assistance had reduced the stress level by five times in comparison to the conventional process. Aeronautical alloy Ti-45Nb has been assisted with ultrasonic vibration to study acoustic softening mechanisms. The study has reported that the amplitude lower than 34 $\mu$m has resulted in the acoustic softening of the material. It had been also noted that amplitude above 46 $\mu$m had resulted in acoustic hardening with the increase of dislocation density. Ultrasonic vibration also improved the grain refinement of metal. Figure 7 shows the ultrasonic vibration-assisted forming process, especially for the riveting mechanism which has been employed by one of the research groups.

Numerical modeling and simulation have also shown that vibration assistance in forming process reduces the material flow stress. Researchers have combined dislocation dynamics and acoustic energy transformation theory to simulate the ultrasonic vibration effect on material performance. Different mechanism of forming has resulted in different acoustic energies.

Al 1050 alloy has been tested for comparison of normal compression and vibration-assisted compression using a 25 kHz frequency setup. The results have shown that ultrasonic vibrations have improved the morphological properties of the alloy and reduced the flow resistance while compression Figure 8. The forming load was reduced when the process was assisted with ultrasonic vibration and the reason for that was observed to be friction reduction and stress superpositioning.

Al6061-T6 alloy has been studied by researchers for the ultrasonic-assisted upsetting-based metal forming process. The results have highlighted that when frictionless conditions were working through ultrasonic assistance had reduced the load requirement by increasing the temperature of the metal. Some of the studies have reported that with the increase of amplitude (up to 2.96 $\mu$m) of ultrasonic vibrations there was an increase in stress reduction level (31.67%). The inter-surface frictional coefficient was observed to be decreased by 40%. Vibration assisted forming grinding gear (VAFGG) a novel process had been proposed by researchers in which it had been reported that with ultrasonic vibration assistance the force required to grind the gear shape was reduced by 40%. Various research studies have reported that the micro upsetting process may also be combined with an ultrasonic
vibration setup for decreasing the flow stress of the material. The study also observed that flow stress of metal may also be decreased by reducing the size of the component as well as increasing the grain size of alloy. The ultrasonic assistance to upsetting proved to be highly beneficial to forming process. The high-frequency vibration has led to the refinement of grains by introducing severe plastic deformations in the MMC. The studies have shown that with high-frequency vibration of ultrasonic waves the grain size of MMC may be refined up to 100–300 nm. Micro grooves are of utmost importance in the case of the optical system. But the formation of microgrooves on resin surface is difficult due to incomplete filling. One of the research studies has developed a novel machine for microgroove development on resin surfaces and named it an ultrasonic-assisted hot-pressing machine. The machine had led to an increase in the efficiency of microgroove formation on the resin surface by decreasing the dynamic viscosity and contact time of resin with the mold. Figure 9 shows the novel ultrasonic-assisted hot-pressing machine for microgroove formation on the resin surface.

Figure 7. Ultrasonic vibration-assisted setup for riveting. Source: Reprinted from Wang et al., Copyright (2021), with permission from Elsevier.

Figure 8. Ultrasonic vibration-assisted compression testing setup. Source: Reprinted from Zhuang et al., Copyright (2015), with permission from Elsevier.

The ultrasonic vibration setup had been combined with a deep drawing process and it was observed that the process had improved the limit drawing ratio (LDR) from 1.67 to 1.83 in case of sheet thickness of 50 mm; 1.75–1.92 in case of sheet thickness 75 mm and 1.83–2 in case of sheet thickness 100 mm. The ultrasonic vibration also reduced the requirement of punch force significantly. Ultrathin high strength sheets of alloys have been tested for mechanical properties such as tensile strength, ductility, etc. by providing ultrasonic vibration to the conventional testing setup. It had been reported that...
with the increase in ultrasonic frequency up to 3.18 μm the ductility of ultrathin sheets had been increased by 25% but changes in the tensile strength were not significant. Similar results were observed for the grain orientation under the tensile testing setup as the changes in the grain orientation were also non-significant in tensile testing.64 Figure 10 shows the tensile testing setup which has been used by researchers at the lab-scale.64

Transverse ultrasonic vibration assistance compression (TUVC) setup has been used to test the behavior of compressive properties of Ti-45alloy which is difficult to destruct or deform. It had been noted that when ultrasonic vibration of 38 μm was given to the compression sample the temperature was raised to 164°C. The ultrasonic assistance in case of compression has led to a reduction in flow stress of the material.65

The hot glass embossing process had been reported by researchers as a novel process to use embossing on glass materials. The process had been assisted with ultrasonic vibrations which led to a reduction in the loading force as well as reduced the chances of failure of the workpiece material while working. Working on glass material is such a difficult task as a small amount of excessive load can damage the glass entirely. The ultrasonic vibration had helped the process to achieve embossing on the glass without any fail.65 The high frequency and power of ultrasonic assistance in forming process sometimes can lead to changes in the geometry of the specimen. One such study has reported that the increasing power of ultrasonic vibration setup up to 1.80 kW had shown a deep impression on the contact surface of the specimen. The high-frequency wave had led to an inverted drum shape at the contact surface.66

The literature survey about metal forming has suggested that with the ultrasonic vibration the material characteristics and testing conditions have been improved whether it is a case of compression, tensile testing, embossing, rolling, or any other metal forming process. Further, the ultrasonic vibrations can lead to significant changes in the material behavior under forming processes when combined with different techniques such as preheating, post-heating, and in-process heating of specimen while under metal forming processes.

**Machining with vibration assistance**

Machining is a part manufacturing process in which metal is gradually removed in the form of chips from the workpiece to get the desired output even when different machining processes are used for manufacturing.12 The machining process is further classified as Metal removal and Abrasion processes, as shown in Figure 11. Sometimes it is difficult to machine hard and brittle materials using conventional machining where high tool wear and lower surface finish affect the life of tool and part.

The traditional machining process can be used in addition to ultrasonic vibrations to lower tool wear and improve surface finish. Vibration assisted machining (VAM) is a modified machining process in which
conventional machining is combined with ultrasonic vibration and can be used to machine hard and brittle materials.

Vibration-assisted machining (VAM) combines repeatability of manufacturing and small vibrations to enhance the manufacturing process. Vibration-assisted machining process allows conventional diamond cutting of various hard materials possible without problems. In recent years vibration-assisted machining has been used in different machining methods like Turning, Milling, Drilling, and Grinding, and it gives promising output results by improvising surface finish and other properties of the material.

**Vibration assisted turning**

While machining components, vibration-assisted machining reduced the deformation zones with increased surface finish and component strength. In recent years industries have been focusing on machining hard materials like hard ceramics alloys vibration-assisted machining is used for cutting ceramics, in which different results have shown promising results. At a frequency of 50 Hz, the volume is increased up to $25 \text{ mm} \times 0.2 \text{ mm}$, and surface roughness is of 1–$6 \mu \text{m}$ is achieved with less rise in temperature of tool and machined workpiece. Applying vibration-assisted turning operation to the aviation materials improved the roughness and roundness of parts with improved results of 25%–50% compared with conventional turning machining. Different Composite materials are also machined using Vibration-assisted Turning like Metal Matrix Composite of aluminum alloy reinforced with SiC particles.

Results have shown that using VAM, there is an improvement in surface roughness compared with simple turning machining. The high surface finish of hard and brittle materials is one of the crucial factors that affect the product’s life. A study of Low steel alloy (DF2) has been conducted using vibration assisted turning and compared with conventional turning results show increased surface finish with low cutting forces required with lower tool wear rate under different cutting conditions.

Most of the hard and high abrasive materials used in aerospace and automobile industries are difficult to machine, and many studies have been already done using vibration-assisted machining in which promising
results were shown. The study and testing have conducted in which aluminum alloy Al2024 with reinforcement of SiC 45% using polycrystalline diamond (PCD) tool were investigated in which various tool geometries and surface finish factors were analyzed, and there is a significant reduction in tool wear under ultrasonic vibrations as compared with the conventional machining.72 Titanium-based alloys are used in propeller manufacturing where metal is exposed to seawater where corrosion will reduce the part’s life, and machining of Titanium-based alloy with lower cooling fluid increases heat generation and affects chip removal.73

**Ultrasonic assisted drilling**

Analysis of Titanium-based alloy Ti6Al4V was conducted using a drilling process in which different parameters were monitored like feed force and chip formation using high-speed cameras with drill tip temperature measurement using infrared thermometry as shown by Figure 12. Ultrasonic assisted machining of Ti6Al4V reduced the feed force by 10%–20% on average, but there was a significant rise in the drill bit’s temperature compared with the conventional machining. Further, an increase in vibration amplitudes gives a higher reduction in cutting forces, and at the same time increase in the temperature of the drill bit was observed. Figure 13 shows the thermal images of the drill bit, giving a clear indication of the rise in temperature while adding ultrasonic vibrations.73

Drilling holes in aviation materials such as titanium and nickel superalloys get burr formation at the cutter ends, higher stresses and high temperature on the drill tool vibration assistance can be used with conventional machining to improve the finish of holes. Studies in recent years have shown that using ultrasonic assistance with conventional machining can improve the cylindricality, circularity, and surface roughness of the drilled hole and achieve up to 60% of improvements.74 Drilled hole samples and drill tool wear samples are shown in Figures 14 and 15, in which we can see the hole drilled using ultrasonic assistance are more accurate than the conventional machining without ultrasonic assistance.

Accuracy and surface finish are the significant factors that affect the quality of the finished product. Researchers have investigated the effects of ultrasonic vibrations combined with drilling on Al/SiCp MMC using TiN coated HSS drill bit of 5 mm diameter. Investigation shows that at 20% SiC content, a lower burr was observed, and a reduction in burr height, surface roughness, and feed force with the application of ultrasonic vibrations compared with conventional drilling.75

Further drilling of superalloy Inconel 718 was conducted with different frequency ranges, and amplitudes results have shown that the best drill life was at a frequency of 31.8 kHz and 4 μm amplitude, and the drill life was enhanced 2.7 times using vibration assistance.7

**Ultrasonic assisted grinding**

Vibration assistance can also be combined with grinding to improve surface roughness and reduce cutting forces. A study of Vibration assisted grinding on Ti6Al4V alloy was carried out in which a range of
20 kHz longitudinal vibrations was applied to the workpiece. Investigation shows a reduction in grinding forces in all Ultrasonic assisted grinding addition with an average reduction in Normal and Tangential forces up to 13.5%, and 14.2% was also observed with improvement in surface finish up to 10% compared with Conventional Grinding.76

Vibration-assisted machining is also having applications in the polymer industry. Ultrasonic vibrations reduce the cutting forces acting upon the surface of the workpiece and tool with minor subsurface damage.77 Under ultrasonic vibrations, relevant experiments on polymers have shown improved machined surfaces, lower cutting forces, and significantly reduced fiber deformation.78

Figure 12. Experimental setup (a) of the machine, details of the sample clamping system (b), and FEM simulation of the axial vibration mode (c).
Source: Reprinted from Pujana et al.,73 Copyright (2009), with permission from Elsevier.

Figure 13. Thermograms of the drill where (a) there is no US assistance and (b) with US assistance captured at sample entering.
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Other studies are also available which have reported the improvement in machining with ultrasonic assistance to machining operations using FEM and numerical modeling approach.\textsuperscript{79–82}

From the literature survey, it has been observed that the combination of vibration to the various machining processes can improve the surface finish of the product reduction in cutting forces. Machining hard material with vibration assistance can reduce the tool wear rate by providing a high surface finish. In several machining operations like drilling, there was a significant rise in temperature due to the increased frequency of vibrations. Further reduction in the temperature of drilling operations can be carried out in future works.

**Welding with vibration assistance**

Vibration assisted welding (VAW) has offered an effective alternative to conventional welding treatments and heat treatment processes to cut down the residual stress and imperfections thereby improving mechanical properties. This section presents a review of various works reported on the application of vibration using different methods and processes to the welding operation. Furthermore, the influence of vibration on microstructure, mechanical properties, and residual stress of welds are also depicted.

To obtain higher joint strength, different methods and processes have been proposed by the authors in the past for similar and dissimilar welds. Zhao et al.\textsuperscript{79} evaluated the mechanical properties of Al/Mg FSW joints under the influence of ultrasonic vibration. The tensile strength, toughness, and crack location for various cases were compared under different welding conditions. 6061-T6 Al alloy and AZ31B-H24 Mg plates were butt welded with an H13 tool at 800 rpm and with welding speeds ranging from 30 to 80 mm/min. The tool depth and angle\textsuperscript{83} were fixed at 0.15 mm and 2.5° as shown in Figure 16. The tests were conducted under normal and vibration-assisted conditions. It was concluded that the implementation of ultrasonic vibration significantly improved the tensile strength of the welds, and the enhancement is more apparent at the middle and lower locations.

Tewari\textsuperscript{84} investigated the tensile properties of carbon steel weld specimens under longitudinal oscillation. The yield strength, ultimate tensile strength, percentage of elongation, breaking strength, impact strength, and hardness were evaluated for the test specimens of 8–12 mm thickness. The percentage improvement of 21%, 26%, and 39% were seen for the welds under oscillations as compared to the normal weld specimens.

Kumar et al.\textsuperscript{85} evaluated the effect of ultrasonic vibration on the mechanical properties of friction welded Al and Mg welds. The parameters include welding speeds ranging from 50 to 250 mm/min with a rotational speed of 600–1200 rpm at a fixed plunge depth of 0.1 mm. The outcomes showed the optimum welding parameters as 800 rpm with 100–150 mm/min welding speed. Welding performed using ultrasonic vibrations showed a 29.32% reduction in welding load and a 22.12% reduction in torque. Furthermore,
augmentation of 37.88% in shear strength was observed corresponding to the 800 rpm at a welding speed of 100 mm/min, whereas insignificant effects on microhardness have been noticed.

Methong and Poopat\textsuperscript{86} evaluated the influence of ultrasonic vibration on the microstructure and properties of carbon steel using a GTAW weld setup (Figure 17). Specimens with a reduced 4 mm diameter were used in this study at fixed welding parameters of 180 A, 15 V, and 151/min of gas flow rate. Welds having ultrasonic vibration at a frequency of 20 kHz, 10–15 \( \mu \text{m} \) amplitude, and 1.4 kW power was tested and compared with specimens without ultrasonic welds. The outcomes of the investigation reported a significant grain refinement in the weld metal and a 43.18% increase in impact energy as compared to conventional welds.

Tewari and Shanker\textsuperscript{87} evaluated the tensile properties of SMAW welds under the influence of longitudinal vibrations. The frequency varied from 0 to 400 Hz, and the amplitude varied from 0 to 40 \( \mu \text{m} \). It was observed that the tensile properties of the welds developed under vibrations in contrast to the static weld specimens. However, a reduction in the percentage elongation was noticed for the weld specimens under vibratory conditions. It was reported that with the increase in frequency, tensile properties improved and the percentage elongation was of decreasing trend.

A novel ultrasonic vibration-assisted friction stir welding ( UVaFSW ) setup (Figure 18) was deployed by Muhhamad and Wu\textsuperscript{88} to lucratively weld aluminum alloy (AA6061) and pure copper (C10100) plates with dimensions of 200 mm \( \times \) 65 mm \( \times \) 2 mm. For both FSW and UVaFSW welds, the rotational speed varied from 400 to 800 rev/min, at a fixed welding speed of 20 mm/min. As per the observations, the strength of the welded joint was increasing up to the rotational speed of 600 rev/min. The highest tensile strength of the Al-Cu joint with the assistance of ultrasonic energy was found to be 124 MPa, which is 13% superior to that of conventional FSW weld.\textsuperscript{88}

Microstructure refinement using ultrasonic vibration-assisted SMAW has been reported by Cui et al.\textsuperscript{89} using 304SS plates. The set-up for the experiment comprises an ultrasonic generator, and
waveguide in addition to the welding apparatus. The vibration enriched the grain structure of weld metal—reducing 95% dendritic to 10%.

In addition to arc welding, laser beam welding using ultrasonic vibration has also been investigated by Kim et al.90 by attaching the ultrasonic vibration to the bottom of the plate (Figure 19). It was realized that cracks and porosities were significantly suppressed by the ultrasonic vibration due to improvement in melting characteristics as seen in Figure 20.

Vibration-assisted welding was reported to be enhancing the impact toughness of the Niomol490K weld in an experimental study by Pucko.91 Results were evaluated against three other weld conditions. It was concluded that the vibration-assisted welding upsurges the energy absorbed in the impact test and improves the rupture behavior. Multi-pass specimens welded with vibration exhibit higher toughness among different cases studied. Fracture surfaces were also visualized which conveyed different pattern types for vibrated and un-vibrated weld specimens (Figure 21).

Microstructure improvement in the case of TIG welding under acoustic effect was also examined by Chen et al.92 The study reported the TIG welds of pure aluminum alloy. Optical microscopy was employed to visualize the grains at weld sections. The effect of ultrasonic amplitude, welding current, and other influencing parameters was studied on the grain structure. The visual outcomes of the grain fragmentation revealed a distorted columnar structure for pure aluminum welds. A finite element simulation was also reported to estimate the acoustic pressure and streaming in the weld pool.

Zhao et al.93 attempted to improve the joint quality of dissimilar alloys by employing ultrasonic vibration. The authors studied the behavior of Al-6061/MgAZ31B welds and a significant effect was noticed on the grain pattern and re-crystallization. The outcomes were discussed using visualization of different locations. Also, it was concluded that the effect of ultrasonic vibrations on the Al alloy side is comparatively little as compared to the Mg alloy side.
Singh et al.\textsuperscript{94} applied vibrations on the SMAW process of 10 mm thick SS202 steel. Under high and low heat inputs, the yield strength, micro-hardness, and ultimate tensile strength were determined and compared with normal welds. It was evident from the metallographic images that a finer microstructure can be attained using vibrations which eventually leads to improved yield strength and ultimate strength.

Liu et al.\textsuperscript{95} exhibited an improved microstructure of butt weld joints created using a friction welding process boosted with ultrasonic vibrations. 2024Al-T4 butt joints were experimentally examined along with metallographic/X-ray visualizations which revealed better microstructure and grains formation. Mechanical testing was conducted at different parameters indicated comparatively augmented performance of joints compared to conventional joints.

Yu et al.\textsuperscript{96} performed lap welding of Al6061/Ti-6Al-4 V and studied their effect on the microstructure and strength. During the experimentations, the ultrasonic frequency of 20 kHz, amplitude ranging 0–20 $\mu$m, the pressure ($P$) in the range of 0.1–0.5 MPa were examined. The welding parameters viz. the rotational and traverse speed were fixed as 1000 r/min and 100 mm/min. It was experimentally discerned that the ultimate shear strength of Al/Ti welds was doubled (225%) as compared to un-vibrated welds. Tool wear was also noticeably eliminated with vibration assistance. Better interfacial bonding was achieved in UV-assisted welds (Figure 22) owing to the vibrations.

Shah and Liu\textsuperscript{97} also reported an enhanced spot welding of 780 and AA606 aluminum which signifies that Al-Fe bonding significantly increases with vibration and reported around 300% augmentation in the tensile strength. TIG welding can also be optimized for enhancing the tensile strength and microstructure. The tensile shear strength showed a 30% increment over the normal weld owing to the ultrasonic vibrations.

Ding and Wu\textsuperscript{98} studied the joint quality by introducing the acoustic effect in friction stir welding (Figure 23). It was witnessed that the torque and axial force on the tool decreases and the overall defects in the weld area decreases significantly. The tensile strength was marginally improved than normal welds and the micro-hardness of UV-assisted welds was higher than the conventional welded joints.

The mechanical behavior of Al6061 FSW joints was explored by Ma et al.\textsuperscript{99} under different ultrasonic
powers. The maximum tensile strength and hardness were achieved at 50% ultrasonic power and the lowest was reported at 90% power output. Amini and Amiri studied the acoustic effect of 20 kHz using Abaqus software and experimentally also revealed a 25% reduction in downward tool force and improved penetration. The augmentation of the order of 10%–15% was attained in the tensile strength and hardness.

Bagheri et al. presented a comparative study of different welding processes with and without vibration assistance. The friction stir vibration welding was found to be most efficient with an efficiency of 81%. Furthermore, the toughness and hardness were also superior for vibration-assisted welding as compared with other processes. Welding load reduction has been reported by making use of novel vibration-assisted friction welding (Shi et al.). Improved joint quality and reduced tool force and torque were achieved by using numerical simulations and were experimentally validated. Similarly, enhanced mechanical properties have been reported by Bai et al.

**Future perspective of ultrasonic assistance in conventional manufacturing processes**

From the past literature, it has been established that the ultrasonic assistance to the conventional manufacturing process viz. casting, welding, forming, and machining processes has led to improvement in the cutting forces, surface morphology, and strength enhancement of the joints, and better mechanical results. Whereas a combination of the material matrix, manufacturing, and ultrasonic assistance process parameters needs to be explored more.

Ultrasonic assistance to the conventional manufacturing process needs to be integrated with the mathematical and numerical modeling techniques so that a better understanding of the impact of processing parameters may be established.
There are very few studies exist that report on the ultrasonic assistance to three-dimensional (3D) printing which is a very interesting topic for today’s researchers where the ultrasonic vibration may lead to better mechanical strength and reduced internal stresses in the components.

**Summary**

The current research has dealt with the review of the different works available for ultrasonic assistance to conventional manufacturing processes. The literature survey of the different techniques has revealed that with ultrasonic assistance manufacturing processes have been improved significantly. It has been observed that ultrasonic assistance in each of the manufacturing processes has led to improved mechanical and morphological properties. Also, ultrasonic assistance has reduced the processing loads with improved material flow stress. Following are the conclusions from the current review study

1. Metal casting with ultrasonic assistance literature has shown that the process reported significant (more than 200%) improvement in the mechanical as well as morphological characteristics. The results were largely observed due to a reduction in the material flow stress and a reduction in the load requirement in the case of forming.
2. As per the literature of ultrasonic assistance in metal forming (tension/compression) has led to a reduction in the load requirement and an increase in the temperature of the component up to 150°C. The temperature increment with ultrasonic vibrations softens the material and improves mechanical performance.
3. Literature on machining has revealed that ultrasonic assistance to the machine setup reduces the cutting force requirements for hard-to-cut materials and improves the surface finish up to the extent of 10%. The ultrasonic vibrations have increased the temperature in the case of drill operations thus reducing the drilling load.
4. Metal joining operations with ultrasonic assistance reported improved quality welds. Further, the microstructure near the weld zone has been observed to be enhanced. In friction welding, it was observed that with vibrations assisted process the tool wear was reduced significantly.

Thus, the current investigations of different manufacturing processes have reported that ultrasonic assistance to conventional processes has been improved up to great extent. Further, the researchers may use ultrasonic assistance for any conventional processes as there are several parameters of the manufacturing process and ultrasonic vibration setup which can be combined to form a new set of inputs.

**Acknowledgements**

The authors are highly grateful to CT University, Ludhiana for providing continuous technical and moral support for the research work.

**Author contributions**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dr. Sudhir Kumar, Dr. Inderjeet Singh, Mr. Dinesh Kumar, and Dr. Debabrata Rath. The first draft of the manuscript was written by Dr. Sudhir Kumar and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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