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Dynamic Performance Evaluation of Ultrasonic Composite Horn for Machining Soft and Brittle Composites

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ABSTRACT

Ultrasonic horn (USH) is a key component in high intensity power ultrasonic systems to enhance vibration amplitude at tool end (VATE). Due to high intensity ultrasonic operating frequency of at least , horn may be exposed to high stress levels leading to failure. The primary objective of USH design is to achieve high vibration amplification with good strength. In present research, the effect of fillet radius / roundness on ultrasonic composite horn (USCH) performance was investigated for various materials: stainless steel, aluminum, titanium, and steel, respectively, using finite element analysis (FEA). USCH was developed for ultrasonic machining of soft and brittle composites, especially Nomex honeycomb composite. The important performance parameters considered were longitudinal modal frequency (LMF), Von Mises (VM) stresses, magnification factor (MF), VATE and factor of safety (FS). LMF was found to increase, with decrease in VATE and VM stresses by increasing the roundness at the transition section. Titanium was observed to be highly appropriate material for USCH, because it delivered at least 81.6 % to 142.62 % more vibration amplification and up to 4 times higher factor of safety, consequently, operating life in comparison to other USCH materials.

Keywords: finite element analysis (FEA); roundness; stresses; ultrasonic composite horn (USCH); vibration amplitude at tool end (VATE).

INTRODUCTION

Advanced soft and brittle composite materials such as Nomex honeycomb composite (NHC) are very popular in aerospace, automotive, biomedical and defence industry and typically used as sandwich structures. Their excellent mechanical and thermal properties such as ultra-lightweight, high strength and high temperature / heat resistance make them highly suitable for these applications (Foo et al. 2007; Zhang et al. 2018; Mughal et al. 2021). Traditional machining techniques such as grinding, milling and drilling usually result in poor machining quality attributes in terms of dimensional accuracy, burr formation, tearing of walls and surface roughness / damage primarily due to softness and brittleness. Likewise, water jet machining (WJM), abrasive water jet machining (AWJM) and diamond saw blade cutting, also, did not provide improved machining quality, surface integrity and dimensional accuracy. To overcome such machining quality related problems, ultrasonic vibration assisted machining (UVAM) is a proven green and sustainable manufacturing technique for such advanced brittle composites (Mughal et al. 2021).

Ultrasonic vibration assisted machining system (UVAM), shown in Fig. 1, typically composes of ultrasonic generator, piezoelectric / magnetostrictive transducer, horn and specialized cutting tool. Low frequency (-) electrical signal is transformed to extremely high frequency electrical signal of at least by ultrasonic generator. Magnetostrictive / Piezoelectric (PZT) transducer converts this high intensity electrical signal to high frequency mechanical vibrations. Vibration amplitude generated by transducer is typically very small (approximately 5 μm) and generally not appropriate for machining of advanced brittle composites (Amin et al. 1995; Mughal et al. 2021). To improve the amplitude of mechanical vibrations, ultrasonic horn (USH) is connected to output end of transducer. To carry out specific machining operation, specialized cutting tool is connected at the smaller end of ultrasonic horn. Application of ultrasonic vibration assisted machining on soft and brittle composites have achieved excellent machining quality attributes along with reduction of forces. (Cong et al. 2014; Ning et al. 2016).

Ultrasonic horn (USH) design to achieve high vibration amplification at tool end (VATE) while keeping stresses at low levels is exciting and challenging. VATE attained by USH should be high enough to achieve good quality machining of soft and brittle composites. Various standard USH designs are available in literature including step, conical, 3rd order Bezier, 3rd order polynomial, catenoidal, Gaussian, 2nd order Bezier and exponential. Every USH design has its own advantages and disadvantages. Greatest vibration amplification can be attained through stepped ultrasonic horn, however with largest stress concentrations at the transition section, forecasting relatively low operating life. Stresses in conical, 2nd order Bezier, exponential, catenoidal and Gaussian ultrasonic horns are low but VATE is also very low in comparison to stepped ultrasonic horn. 3rd order Bezier horns provide reasonably good VATE with low stress concentrations, but at the expense of high design and fabrication cost (Mughal et al. 2021).

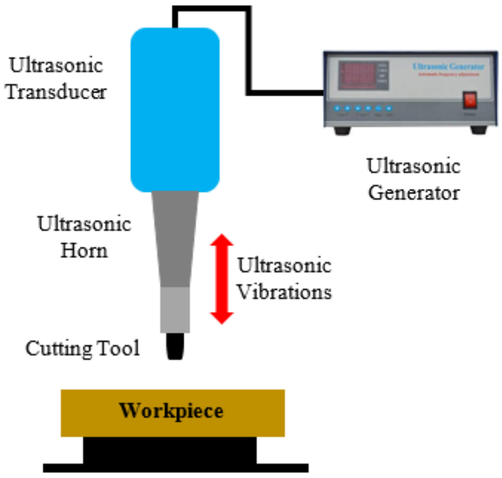


FIGURE 1. Ultrasonic Assisted Machining System

Various geometries have been used in the design of ultrasonic horns for achieving better vibration characteristics in terms of high VATE and low stresses. Wang et al. (2011) used 3rd order Bezier profile in their horn design for ultrasonic welding application. VATE and stresses attained by Bezier ultrasonic horn were found to be less than stepped ultrasonic horn. Nguyen et al. (2014) used non rational B spline profile in their horn design. The stresses and VATE were observed to be closer to stepped ultrasonic horn, but at the expense of very high time and computation effort. Razavi et al. (2019) analyzed forced and free vibration characteristics of five element composite horn for ultrasonic surface rolling application. Yu et al. (2020) performed tuning and eigenfrequency characterization of aluminum alloy (Ti6Al4V) ultrasonic horn for glass molding at elevated temperatures. Cao et al. (2020) carried out performance analysis of novel ultrasonic vibration plate horn for grinding application. Pang et al. (2020) analyzed the influence of spiral slots' geometric parameters on longitudinal-torsional coupled (LTC) vibration characteristics of stepped horn for ultrasonic machining of hard materials. Yu et al. (2020) developed novel horn for mechanically enabled dual axis ultrasonic-assisted machining system. Rai et al. (2020) studied various kind of stresses induced in 2nd order and 3rd order Bezier horns for rotary ultrasonic machining application.

Mughal et al. (2021) designed and analyzed novel ultrasonic horn for machining advanced brittle materials to attain extremely high amplitude of vibration at tool end. They investigated the vibration characteristics of standard ultrasonic horns for frequency ratio less than one. Other horn designs have been attempted to reduce stresses while keeping the amplitude of vibration in acceptable limits (Rosca et al. 2015; Mughal et al. 2021). Mughal et al. (2022) investigated the effect of uniform cutout on the performance of ultrasonic horn suitable for the machining of Nomex honeycomb composite. They varied cutout diameter in non-uniform horn geometry to investigate the influence on resonant frequency, vibration amplitude, stresses, magnification factor and factor of safety. They found increase of axial stiffness, modal frequency and factor of safety, while drop of magnification factor and amplitude of vibration at tool end by increasing cutout diameter. Ouyang et al. (2022) designed and optimized stepped ultrasonic horn having 3rd order B-spline profile at step location using orthogonal technique for micro-injection molding application.

Primary focus of present research work was to investigate the harmonic excitation response of ultrasonic composite horn (USCH) machining of soft and brittle composites especially Nomex honeycomb composite. Merits of both stepped conical profiles such as high vibration amplification attained by former and low stress concentrations in the latter were utilized. The harmonic excitation response performance of USCH was investigated by varying roundness at the transition section. Various research efforts have been made by researchers related to ultrasonic horn design and performance analysis. However, the harmonic excitation response characteristics of ultrasonic composite horn (USCH) having roundness at transition section have never been investigated in terms of vibration amplitude at tool end (VATE), magnification factor (MF), Von Mises (VM) stresses, longitudinal modal frequency (LMF), longitudinal stiffness (LS) and factor of safety (FS). In this regard, finite element analysis was performed to investigate influence of roundness at transition section on USCH performance characterizes. Effect of frequency ratio on VM stresses, safety factor and magnification factor was also examined. Harmonic excitation response analysis of USCH is challenging analytically, while experiments would be time consuming and costly. Thus numerical computations were attempted to investigate the effect of varying roundness at transition section on USCH performance characteristics. Outcomes of present research can be useful for researchers, designers and manufacturers of ultrasonic assisted machining system.

GOVERNING EQUATIONS

Acoustic longitudinal waves propagation in USCH can be expressed by Webster's equation.

$$\frac{\partial^2 u(x,t)}{\partial x^2}+\frac{\partial^2 u(x,t)}{\partial x^2}\frac{\partial}{\partial x}\ln A(x) = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2} \quad (1)$$

Here $c=\sqrt{E/\rho}$ is longitudinal wave propagation speed USCH. For simple harmonic motion (SHM) above mathematical model can be presented as

$$\frac{\partial^2 u(x,t)}{\partial x^2}+\frac{\partial^2 u(x,t)}{\partial x^2}\frac{\partial}{\partial x}\ln A(x) = \frac{\omega^2}{c^2}u(x,t) = {k_1}^2 u(x,t) \quad (2)$$

$k_1=\omega/c$ is circular wave number. USCH displacement at required time and position can be obtained through solution of above equation.

$$u(x,t) = (C_1\sin K_1 x + C_2\cos K_1 x)/\sqrt{A(x)} \quad (3)$$

$u(x,t)$ is particle displacement function in terms of time t and axial position x, $A(x)$ is cross-sectional area, C_1 & C_2 are parameters dependent on system's initial conditions and K_1 is a factor dependent on k, A and x. Von Mises (VM) stress can be computed from in terms of principal stresses σ_1, σ_2 and σ_3.

$$\sigma_{VM}=\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{0.5} \quad (4)$$

USCH factor of safety (FS) is calculated by (5) in terms of maximum VM stress σ_{VM} and material's yield stress σ_Y.

$$FS = \sigma_{VM}/\sigma_Y \quad (5)$$

Magnification factor M of USCH can be computed by (6) in terms of transducer end displacement TED and amplitude of vibration at tool end $VATE$.

$$MF = VATE/TED \quad (6)$$

PROBLEM FORMULATION

Being a continuous system, ultrasonic composite horn (USCH) have infinite vibration modes. Determination of USCH performance characteristics related with desired mode of vibration is complex. For validation of numerical computations the results and realizing USCH performance characteristics comprehensively at generator excitation frequency of 20 *kHz*, USCH was modeled as a single degree of freedom (SDOF) un-damped mass-spring system as presented in Fig. 2. Longitudinal stiffness k of SDOF system, while lumping mass m at end, can be calculated using (7) (Mughal et al. 2022). Ultrasonic vibration assisted machining (UVAM) systems typically utilized for composite processing operate at 20 *kHz* excitation frequency for smooth working, sufficient quality and vibration amplification (Mughal et al. 2021).

$$k_{th} = AE/L \quad (7)$$

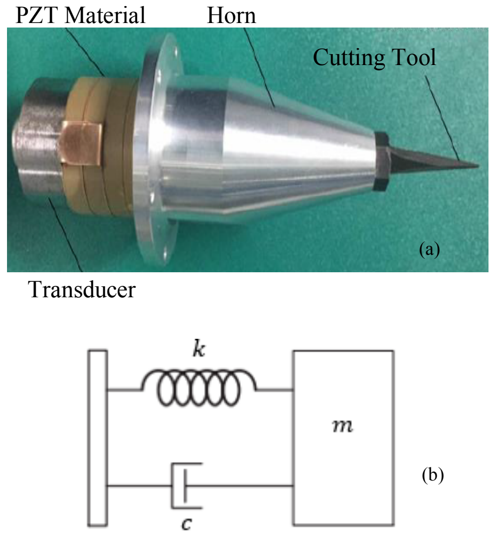


FIGURE 2. a) Ultrasonic Assisted Cutting Tool and b) Equivalent SDOF Mass Spring System (Ke et al. 2019)

Mass of ultrasonic horn with uniform cross-sectional area A, volume V, density ρ and length L can be calculated through $m=\rho V=\rho AL$. Longitudinal modal frequency ω_n of SDOF system can be determined by (8).

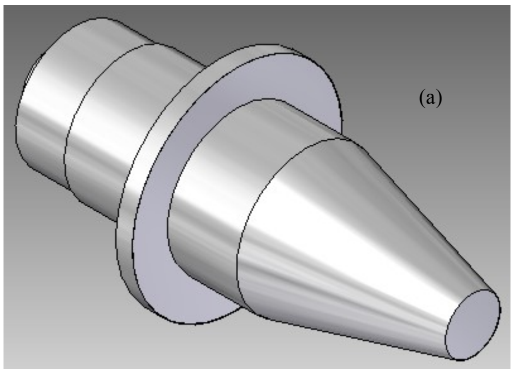
$$\omega_{n_{th}}=\sqrt{\frac{k}{m}}=\sqrt{\frac{AE/L}{\rho AL}}=\sqrt{\frac{E}{\rho L^2}} \quad (8)$$

Analytical magnification factor M_{th} of SDOF systems demonstrating undamped vibrations can be computed through (9) (Rao 2016).

$$M_{th}=\sqrt{\frac{1+\left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}} \quad (9)$$

METHODOLOGY

Primary emphasis of present research work was to explore the influence of varying the roundness at the transition section (step location) of ultrasonic composite horn (USCH) used in the processing of soft and brittle materials specially Nomex honeycomb composite. At first stage, three dimensional (3D) geometric CAD model of USCH was developed in Solid Works SP5.1 (Dassault Systemes) as presented in Fig. 3 (Ke et al. 2019; Mughal et al. 2022), along with the geometry having rounded profile. Investigations were carried out on four different USCH materials including stainless steel (SS), aluminum (Al), titanium (Ti) and steel (S), with properties listed in Table 1. Fillet radius / roundness at the transition section was varied from 0 *mm* to 12 *mm*. USCH dimensions were kept exactly same for all materials, to have an impartial assessment of vibration characteristics including longitudinal modal frequency (LMF), Von Mises (VM) stresses, vibration amplitude at tool end (VATE), factor of safety (FS) and strength.



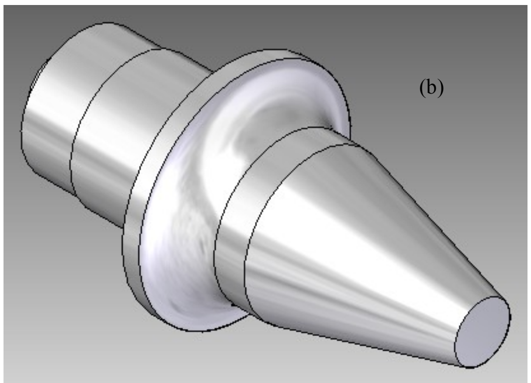


FIGURE 3. Ultrasonic Composite Horn (USCH) Models, (a) without roundness, (b) with roundness

USCH 3D CAD models were imported to ANSYS 16.0 to carry out harmonic and modal analyses for investigating harmonic excitation response at 20 *kHz* operating frequency of ultrasonic tool. Harmonic analysis was conducted using Harmonic Response Analysis System to compute VATE, VM stresses, MF, FS and strength. Modal analysis was carried out using Modal Analysis System to determine LMF and mode shapes. The longitudinal displacement amplitude provided by piezoelectric (PZT) transducer was considered equal to (Mughal et al. 2021). Among infinite Eigen frequencies and mode shapes linked to USCH, longitudinal Eigen frequency was given preference due to longitudinal harmonic excitation of ultrasonic tool. After computing the vibration characteristics associated with the harmonic excitation response of USCH, numerical results were compared for different materials and roundness levels to draw meaningful conclusion.

TABLE 1. USCH materials' properties.

Properties	Stainless Steel	Titanium	Aluminum	Steel
Yield Strength	215	830	280	250
Poisson's Ratio	0.31	0.36	0.33	0.3
Density	7750	4620	2770	7850
Elastic Modulus	193	96	71	200

RESULTS AND DISCUSSION

MODAL ANALYSIS

To extract ultrasonic composite horn (USCH) eigenfrequencies, modal analysis was carried out. Longitudinal modal frequency was given preference due to its importance in ultrasonic vibration assisted machining system. Longitudinal modal frequencies (LMF) of USCH without roundness for various materials were computed first numerically. LMF for stainless steel, titanium, steel and aluminum USCHs were computed to be 23002 *Hz*, 21162 *Hz*, 23236 *Hz* and 23399 *Hz*, respectively. Despite of similar size and shape, LMFs were different for each USCH material due to dissimilar density ρ and elastic modulus E, that influenced mass m and longitudinal stiffness k and of the horn respectively (Mughal et al. 2021). Aluminum horn's LMF was greater in comparison to other horns due to very low mass and relatively less stiffness. Both steel and stainless steel horns had not so different LMFs due to nearly similar and high stiffness and mass. Titanium USCH was found to have least LMF because of moderate mass and relatively less stiffness.

In the similar fashion, LMFs and longitudinal stiffness were computed for USCH by varying the roundness at the transition section. Variation of LMFs of USCHs for various roundness levels and materials is shown in Fig. 4. LMF for all horns was found to increase with the increase of roundness. This behavior was attributed to the reduction of USCH mass with little variation in stiffness as depicted in Fig. 5. This increasing trend in LMF was shown by each USCH material.

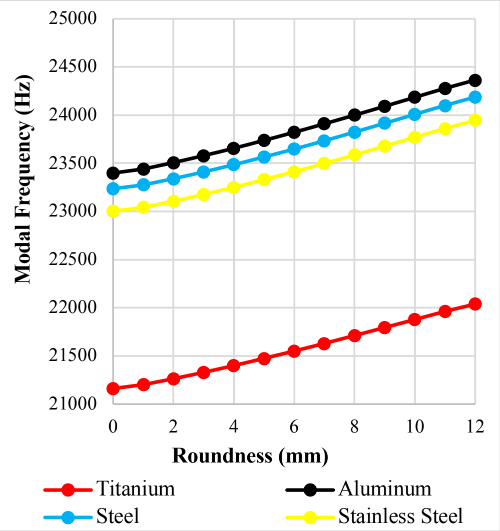


FIGURE 4. Variation of Modal Frequency With Roundness for USCHs

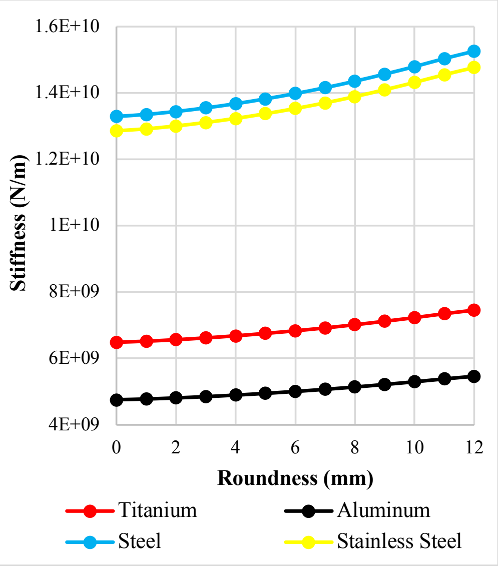


FIGURE 5. Variation of Stiffness with Cutout Diameter for Ultrasonic Horns

HARMONIC ANALYSIS

After computing LMF and mode shapes though modal analysis, magnification factor (MF), vibration amplitude at tool end (VATE), Von Mises (VM) stresses and factor of safety (FS) of USCH were numerically computed using harmonic analysis. VM stresses were computed and given preference due to ductile nature of materials considered in this research at given working conditions. VATE were computed to be 28.602 μm, 69.39 μm, 26.751 μm and 25.567 μm, for USCH without roundness made of stainless steel, titanium, steel and aluminum, respectively. VATE achieved by USCH is highly dependent on the ratio of forcing frequency ω to natural frequency ω_n (frequency ratio ω / ω_n). The longitudinal modal frequency (LMF) of each USCH was different from each other and from 20 *kHz* harmonic excitation frequency. Due to this reason, VATE achieved by each USCH was different. Highest VATE was attained through titanium USCH due to closeness of its LMF with the ultrasonic generator's excitation frequency. VATE is largest at frequency ratio equal to one i.e. resonance, the condition at when the LMF of ultrasonic tool becomes equal to ultrasonic generator's excitation frequency ($\omega = \omega_n$) (Mughal et al. 2022).

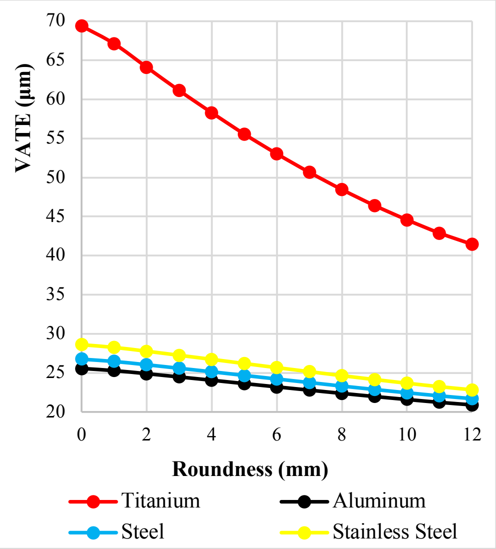


FIGURE 6. Variation of Vibration Amplitude at Tool End (VATE) with Roundness for USCH

Decrease in VATE was observed with the increase of roundness at the transition section of USCH for all materials as indicated in Fig. 6. Reduction of VATE with the increase of roundness in stainless steel, aluminum and steel horns were observed to be less in comparison to significant drop in titanium horns. This occurred due to significant difference of LMFs of stainless steel, aluminum and steel horns from the 20 *kHz* harmonic excitation frequency of ultrasonic generator. Increase in roundness further enlarged that frequency difference resulting relatively less VATE reduction. On the other side, enlarging roundness at transition section of titanium USCH caused increase in LMF to 22.04 *kHz* for roundness of 12 *mm* radius, that resulted in a drop of 40.26 % from 69.39 μm to 41.45 μm (for USCH without roundness). In similar fashion, reduction in magnification factor (MF) was observed with the increase of roundness at transition section of USCH for all materials as shown in Fig. 7. MF reduction of 20.17 % (from 5.72 to 4.57), 18.24 % (from 5.11 to 4.18) and 18.87% (from 5.35 to 4.34) for stainless steel, aluminum and steel horns, respectively, while increasing the roundness up to 12 *mm* radius.

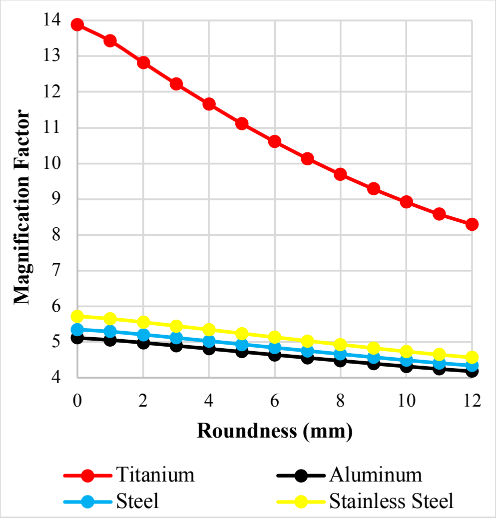


FIGURE 7. Variation of USCH Magnification Factor with Roundness

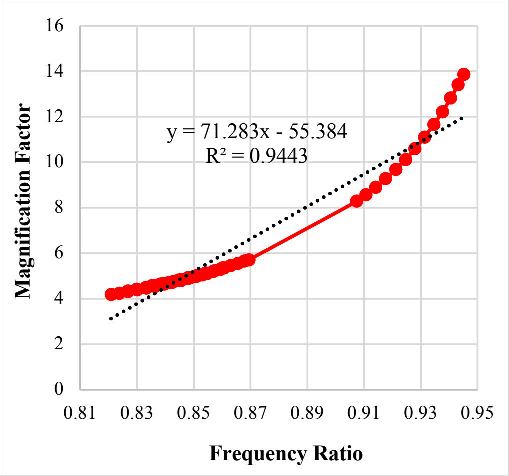


FIGURE 8. USCH Magnification Factor Variation with Frequency Ratio

Drop of VATE can be described appropriately by noticing the variation of magnification factor (MF) with frequency ratio for all USCH models as presented in Fig. 8. Increase in magnification factor was observed as a result of increasing frequency ratio up to the resonant condition at frequency ratio equal to 1. Ahead of resonant condition, magnification factor is expected to decrease as a result of increasing frequency ratio (Rao 2016). Regression analysis and high correlation coefficient (R^2 = 0.932) pointed out extremely strong relationship between frequency ratio and magnification factor. This indicated that majority of magnification factor variation could be explained conveniently by taking frequency ratio into consideration.

STRESS ANALYSIS

After computing LMF, longitudinal stiffness (LS) VATE and MF, Von Mises (VM) stresses developed in USCH for various roundness levels and materials were determined numerically at 20 *kHz* harmonic excitation of ultrasonic generator. VM stresses developed in stainless steel, aluminum, titanium and steel USCHs were found equal to 145.86 *MPa*, 46.994 *MPa*, 186.65 *MPa* and 140.23 *MPa* respectively. Significant reduction of VM stresses were observed with the increase of roundness for all USCH materials considered in this research as presented in Fig. 9. High stress concentrations were observed in titanium USCH with largest VM stress equal to 232.67 *MPa* for roundness of radius. VM Stresses were decreased to a magnitude of 78.81 *MPa* for titanium USCH having 12 *mm* radius, indicating 57.8% stress relief. For stainless steel and steel USCHs, largest VM stresses were found at roundness of 1 *mm*, equal to 178.61 *MPa* and 170.86 *MPa*, respectively. VM stresses were reduced to 81.6 *MPa* and 79.73 *MPa* at 12 *mm* roundness indicating stress relief of 41.8 % and 40.73 % for both USCHs, respectively. Significantly less VM stresses were generated in aluminum USCHs with largest stress equal to 58.41 *MPa* at roundness of 1 *mm* radius while minimum VM stress equal to 26.73 *MPa* at 12 *mm* roundness. Stress relief of 40.73 % was observed in aluminum USCH by incorporating roundness.

The magnitude of stresses cannot decide the strength and operating life of USCH alone. Extremely low stress concentrations in aluminum USCH cannot guarantee its high suitability for ultrasonic machining application. Whereas high stress concentrations in titanium USCH does not indicate its unsuitability for horn design in ultrasonic applications. Stresses in ultrasonic systems are typically largest at resonant condition ($\omega/\omega_n = 1$). stresses developed in titanium USCHs considered in present research were found to be greater due to their LMFs closer generator's excitation frequency.

Moreover, the stresses in such USCHs are typically dynamic in nature, consequently they are not governed by frequency ratio alone. Scatter plot of VM stresses for various frequency ratios considering USCH materials and roundness is presented in Fig. 10. Regression analysis delivered better insight into dependency of stresses on frequency ratio. Regression plot and correlation coefficient R^2 = 0.42 indicated that the variation of stresses cannot be explained by frequency ratio only. Other USCH parameters including acceleration, mass, geometry and dynamic forces also effect the resulting stresses.

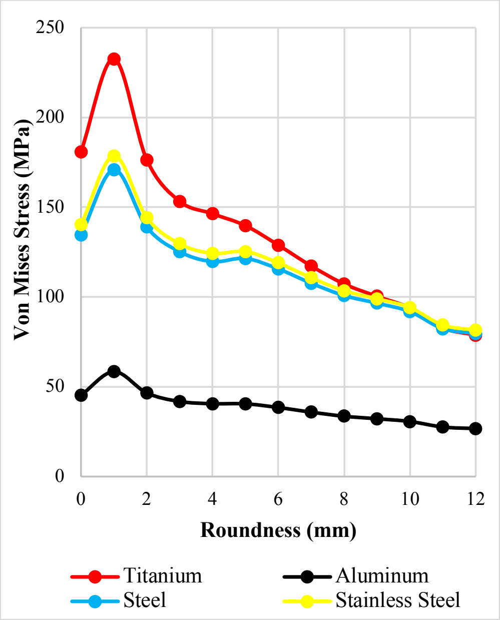


FIGURE 9. Variation of VM Stresses with Roundness for USCH

As four different materials under consideration in present work have dissimilar yield strengths, for that reason VM stresses are not the sole indicators of USCH operating life. Material's yield strength and maximum VM stress were used to compute factor of safety (FS), whose variation with roundness at USCH transition section is plotted in Fig. 15. Stainless steel, aluminum, titanium and steel USCHs were found to have factor of safety up to 2.63, 10.47, 10.53 and 3.14, respectively by setting roundness equal to 12 *mm*. Although steel and stainless steel horns were designed with LMFs away from generator's excitation frequency, their safety factors were found comparatively lower than those of aluminum and titanium USCHs. Their factors of safety are expected to further decrease when they would be designed to have LMFs closer to excitation frequency.

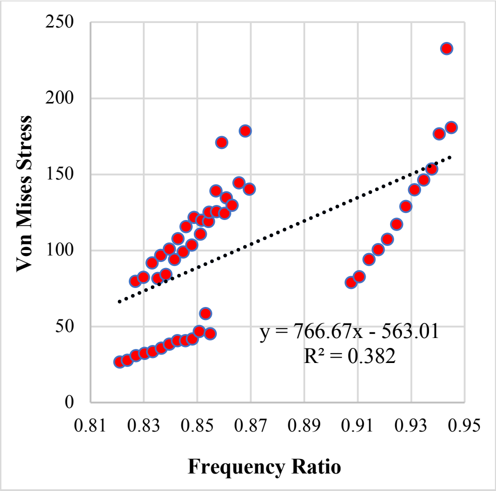


FIGURE 10. VM Stress Scatter Plot Vs Frequency Ratio for USCH

Safety factors of aluminum USCHs were found in between 6.18 and 10.47, while those of titanium USCHs were found in the range of 4.59 and 10.53, under similar operating conditions, projecting high operating life. For specific operating conditions, materials and range of factors considered in present work, factor of safety, hence operating life were found to enhance, typically, with producing more roundness at the transition section of USCH.

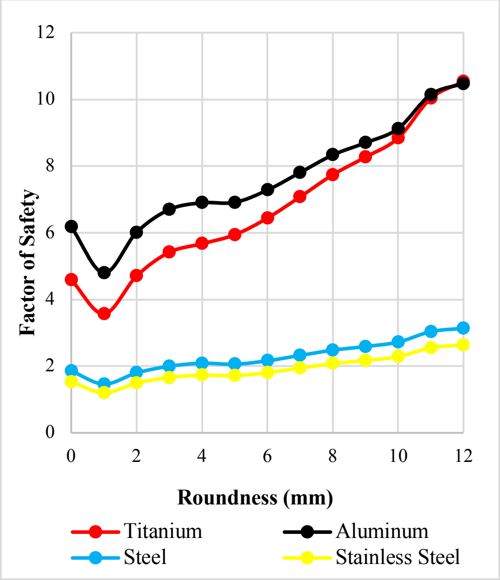


FIGURE 11. Variation of Factor of Safety with Cutout Diameter for Ultrasonic Horns

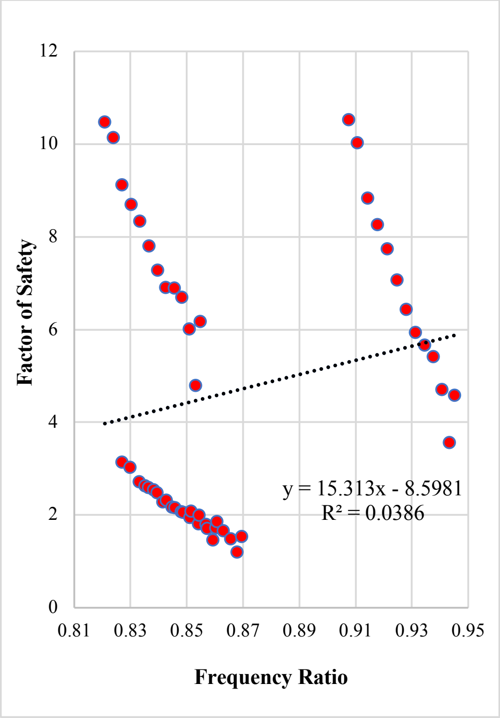


FIGURE 12. Scatter Plot of Factor of Safety Vs Frequency Ratio for USCH

Aluminum USCHs were observed to have LMFs far away from 20 *kHz* excitation frequency of generator in the axial direction distinct from operating frequency of generator, which resulted in relatively higher factor of safety and low stresses. Design modifications in aluminum USCHs to set LMFs closer to excitation frequency would cause stresses to increase consequently resulting reduction of safety factor. Titanium USCHs were found to have LMFs closer to excitation frequency of generator that caused high stress concentrations as compared to other USCHs. Since titanium has very high yield strength, therefore the safety factor and consequently operating life of corresponding USCHs were found to be superior. Design modifications in titanium USCHs to achieve LMFs away from excitation frequency would further enhance factor of safety and operating life while reducing stresses, indicating better performance. Fig. 12 presents scatter plot of safety factor against frequency ratio for all USCH models considered in current research. Regression analysis and low value of correlation coefficient ($R^2 = 0.0386$) pointed out that variation of factor of safety could not be elucidated by frequency ratio only. USCH factor of safety is also influenced by other factors including acceleration, mass, geometry, material properties and dynamic forces.

Harmonic excitation response performance comparison of ultrasonic composite horn (USCH) with roundness of 12 *mm* radius is presented in Fig. 13. Greatest vibration amplitude at tool end (VATE), magnification factor (MF) and safety factor were achieved by titanium USCH among all horn materials considered in present research. Harmonic excitation response performance comparison of USCH with and without roundness at step location (Fig. 14) showed reduction of VATE with increase of safety factor and consequently operating life by incorporating roundness.

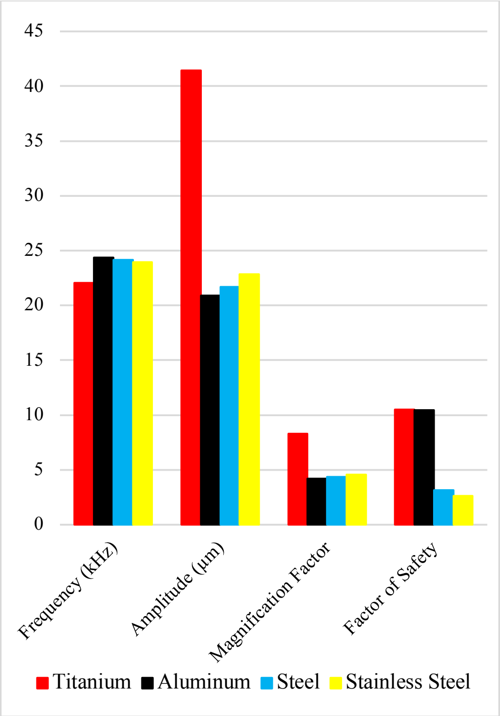


FIGURE 13. Comparison of USCH Performance with 12 mm Roundness for Various Materials

Finite element simulation results regarding harmonic excitation response performance of USCH were validated through comparison with theoretical expectations by taking into account the simplified USCH model. Finite element simulation results of magnification factor with theoretical magnification factor is shown in Fig. 15 for USCH without and with 12 *mm* roundness. Good agreement of finite element simulation results and theoretical expectations was observed. Though, dissimilarity in magnitudes was apparent resulting from USCH model simplification. The summarized results regarding harmonic excitation response performance characteristics of USCH in terms of LMF, VATE, magnification factor (MF), VM stresses and factor of safety (FS) by varying the roundness at step location are presented in Table 2.

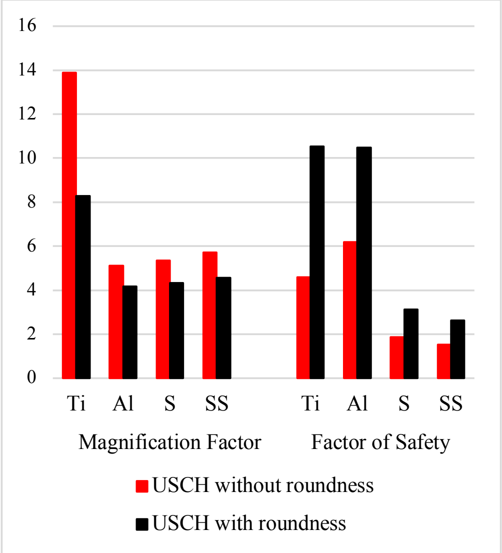


FIGURE 14. Comparison of USCH Performance without and with 12 mm Roundness

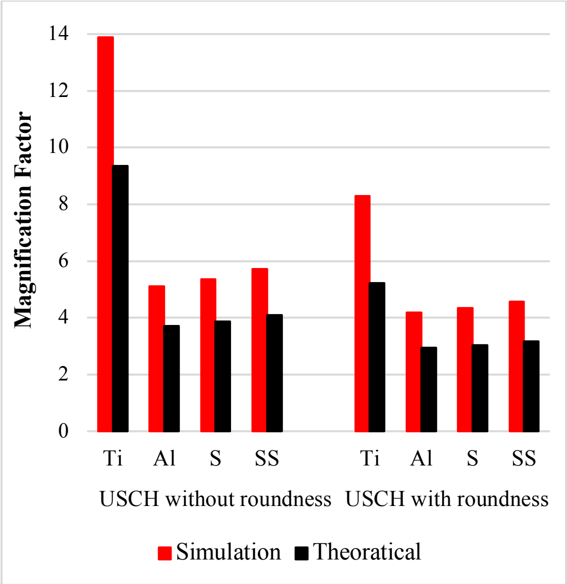


FIGURE 15. Comparison of Simulated and Theoretical Magnification Factors for USCH without and with 12 mm Roundness

TABLE 2. Summarized Results of Effect of Increasing Roundness on USCH Performance Parameters

Performance Parameter	Aluminum	Steel	Stainless Steel	Titanium
Horn Mass	↑	↑	↑	↑
Modal Frequency	↑	↑	↑	↑
Axial Stiffness	↑	↑	↑	↑
Amplitude of Vibration	↓	↓	↓	↓
Magnification Factor	↓	↓	↓	↓
Stress	↓	↓	↓	↓
Factor of Safety	↑	↑	↑	↑

CONCLUSION

The present research work was concentrated on investigating the influence of varying roundness at the transition section on the performance of ultrasonic composite horn (USCH) for machining soft and brittle composites. Ultrasonic composite horn was designed accordingly by utilizing the advantages of both conical and stepped horns, roundness was varied at step location with radius up to 12 mm. Numerical investigations were performed using finite element analysis of USCH for various isotropic materials such as stainless steel, aluminum, titanium and steel. Good agreement of simulated harmonic and modal analyses results with theoretical expectations was observed. Following conclusions were drawn after intensive numerical computations regarding design and dynamic performance of USCH for frequency ratio greater than one ω/ω_n.

- Longitudinal modal frequency (LMF) usually increases with increase of roundness at step location for all materials.
- Longitudinal stiffness of USCH enhances with increase of roundness at step location for all materials.
- Vibration amplitude at tool end (VATE) and consequently magnification factor (MF) drops with the increase of roundness at step location for all materials.
- VM stresses usually decrease while factor of safety improves by increasing roundness at step location for all materials.
- Under given operating conditions, titanium USCHs attained largest MF and VATE, whereas aluminum USCHs experienced least VM stresses primarily due to their low mass. Titanium's yield strength is significantly greater in comparison to aluminum and steel materials, guarantying relatively high operating life due to high factor of safety. Hence, titanium is preferable for design of efficient and high performance USCH due to excellent acoustic characteristics.
- Aluminum can be selected as an alternative material for USCH design owing to reasonable vibration amplification, least stresses and good operating life, due to high cost associated with titanium USCH.
- Optimum vibration characteristics in terms of high vibration amplification and reasonably good safety factor were achieved by USCH designs without roundness.
- High VATE of ultrasonic tool and low stress concentrations are helpful to achieve better machining quality, dimensional accuracy, high material removal rate along with clean and sustainable environment. These attributes distinguish UVAM from other conventional / non-conventional machining processes and make this technology highly suitable to process soft and brittle composites for industrial applications.
- Findings of this research would be extremely valuable for designers, researchers and manufacturers of ultrasonic cutting machine for soft and brittle composites to realize improved machining efficiency, quality and material removal rate.

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DECLARATION OF COMPETING INTEREST

None

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