Proceedings of the 7th International Conference on Mechanics and Materials in Design
Albufeira/Portugal 11-15 June 2017. Editors J.F. Silva Gomes and S.A. Meguid.
Publ. INEGI/FEUP (2017)

PAPER REF: 6433

EFFECTS OF AMBIENT PRESSURE AND FLUID TEMPERATURE IN ULTRASONIC CAVITATION EROSION

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ABSTRACT

One of the prevalent material removal mechanism in vibratory ultrasonic machining (USM) is cavitation erosion. Cavitation erosion is the process of surface modification by generation and collapse of vapor bubbles on the workpiece surface inside a liquid medium. Although considerable research has been devoted in finding the material removal mechanism, rather less attention has been paid on the effect of pressure and temperature in cavitation erosion. Hence, efforts have been taken in this investigation to investigate the effects of pressure and fluid temperature on AISI 304 stainless steel with wire cut EDM surface in material removal and surface roughness. Ambient pressure and temperature were varied from 100 kPa to 400 kPa and 10°C to 90°C respectively. The outcomes showed that mass loss increased up to 300 kPa and remained steady at 400 kPa; by varying temperature mass loss showed a peak up to 0.8 mg at 50°C and then declined to 0.2 mg with increase in liquid temperature. Scanning electron microscope (SEM) images showed that most of the test surface deformed plastically with surface undulations. These surface undulations improved the surface roughness values from ranges of 2 µm to 1 µm. A maximum change in surface roughness of 34% at 300 kPa and 36% at 50°C was observed.

Keywords: cavitation erosion, surface roughness, bubble population, ultrasonic.

INTRODUCTION

Vibratory ultrasonic machining is a non-contact manufacturing process that utilizes high frequency, low amplitude vibrations to expel material from the work piece surface. A majormaterial removal mechanism in vibratory ultrasonic machining is cavitation erosion (Karunamurthy, 2010). Cavitation erosion is a process of surface modification due to generation and collapse of vapor bubbles on the workpiece surface. The vapor bubbles are formed when the hydrostatic pressure of liquid falls well below the saturation vapor pressure (3.169 kPa at 25°C (Young, 1999). The pressure difference in the liquid in USM is caused by a vibrating tool excited by a piezoelectric transducer. During this process, the bubble collapse exerts high pressure shock waves (Shchukin, 2011) and micro jets on the workpiece surface thus removing material. In recent years, material removal characteristics in cavitation erosion is widely studied by many researchers (Hammitt, 1980, Hattori and Itoh, 2011, Kwok, 2006). Studies prove that material removal rate in cavitation erosion is dependent on material strength and hardness. Many investigators have studied the erosion mechanism on common engineering materials (Drozdz, 2007, Laguna-Camacho, 2013). It is also proved that mass loss is higher in the presence of abrasive particles suspended in the liquid medium. These led to formation of erosion pits in the workpiece surface (Dular, 2013). These studies were useful in developing non-contact machining methods like drilling hard and brittle materials and surface modification applications.

Despitevarious research efforts in USM, still there exists a need to understand the underlying mechanisms in material removal for increasing productivity and for reducing the effort in machining. To predict the relation between material removal, frequency and amplitude, developed a static ultrasonic machining model. However, the model shows clear discrepancies with experiment results (Shaw, 1956). It is well known that ambient pressure and fluid temperature influences material removal rate in USM. (Young and Johnston, 1970) investigated the effect of pressure and temperature in cavitation erosion. Results show that material removal rate is higher at maximum pressure and temperature conditions. However, the relation between pressure and temperature in cavitation erosion remains unclear. (Li, 2014) investigated the erosion behavior of 304 stainless steel at various temperatures and showed an increase in material removal rate near 50°c and declined with further increase in temperature.

(Ahmed, 1998) investigated the effect of pressure and temperature in cavitation erosion in pure aluminium and found that the number of bubbles formed was large at high temperatures. SEM images obtained by Abouel et.al after cavitation erosion on 304 stainless steel shows erosion pits and cavitation bubble collapse. Bubble collapse leads to plastic deformation and formation of wavy undulations (Abouel-Kasem, 2009). However, there is no clear explanation on the undulation phenomenon caused by cavitation erosion. Thus, controlling these surface undulations will help in enhancing the surface roughness using cavitation erosion.

Stainless steel is often used as pipe and pressure vessel materials for high temperature and high pressure applications. These vessel materials are often prone to failure due to erosion. The liquid medium at high pressure and temperature causes erosion in the vessel structure. Erosion occurs due to irregularities in the metal surface. These irregularities often act as cavitation generators. Cavitation generated at these irregularities erodes the surface material over a long run. Hence, these structures demand a better surface roughness and are often prone to damage by erosion (Lister, 1987). It seems, therefore, that further investigations are required at high pressure and temperature conditions to study their effect in material removal rate and surface roughness characteristics.

Hence, in this study AISI 304 stainless steel with an EDM surface is directly subjected to cavitation erosion at high ambient pressure and fluid temperature conditions. The investigation is carried to study the effect of ambient pressure and temperature in material removal rate and the bubble population during cavitation erosion. The study also examines the SEM images of EDM cut surface before machining and surface undulations produced after machining.

EXPERIMENTAL METHODOLOGY

The specimen surface is initially prepared for machining using Excetek 850 wire cutting EDM machine. The directly cut EDM surface is now exposed to USM as stated in ASTM G32-16 standard at various ambient pressure and temperature conditions. Based on mass loss and surface roughness measurements effect of ambient pressure and temperature on cavitation erosion in USM was investigated. Overall microscopic surface topographies of the specimens from SEM images were also used to analyse the effect of cavitation erosion after machining.

Experiment set-up

The set-up used for USM is shown in Figure 1. The setup consists of an ultrasonic generator (Dukane 4100 benchtop controller) of 40 kHz frequency with a vibrating amplitude of 70 µm. The ultrasonic horn with a tip diameter of 5 mm is made to vibrate using piezoelectric transducer. The constant temperature bath is then filled with deionized water and the test specimen (AISI 304 stainless steel of dimension 15*15*2.5 mm) was placed in the specimen holder inside the bath. Deionized water is used for the study rather than tap water to have controlled amount of impurities and maintain a pH level as specified in ASTM G32-16 standard. The horn is inserted into the liquid medium to a depth of 5 mm from the top surface.

The stand-off distance between horn tip and workpiece surface was fixed at 1 mm for all test conditions. The bath is held air-tight and the test chamber is pressurized according to test conditions. It was ensured that the temperature is maintained constant using the temperature bath and monitored using a thermometer inside the test chamber. Pressure inside the test chamber was monitored using a pressure gauge fixed to the test chamber.

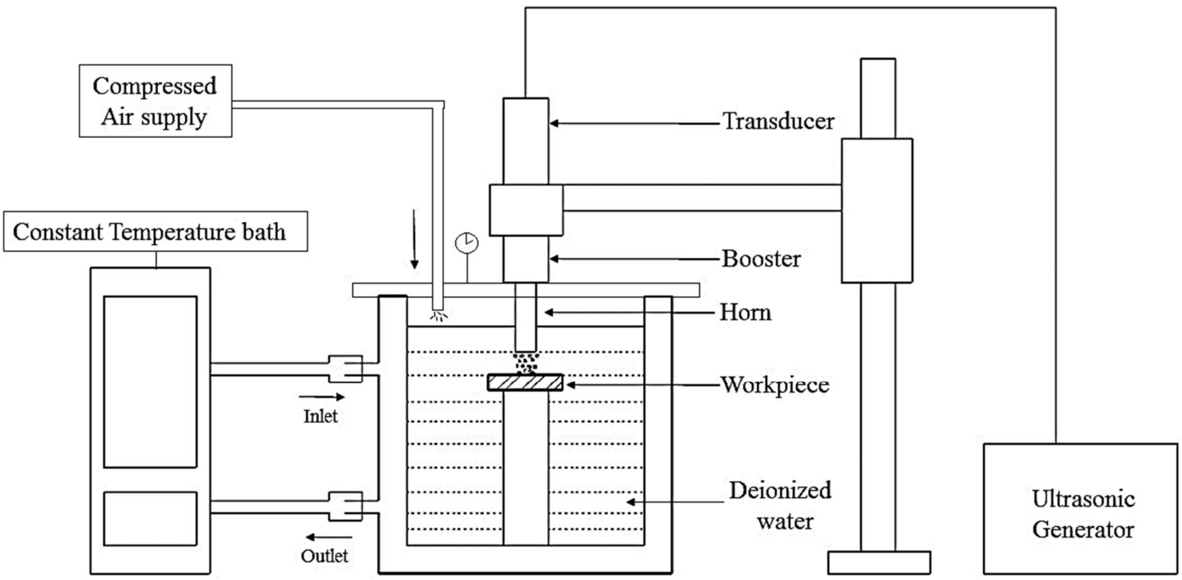


Fig. 1 - Schematic diagram of experimental set-up

Experiment procedure

Initially, the specimens were subjected to ultrasonic cleaning for 10 minutes to remove surface impurities. Then SEM images, mass of the specimen and surface roughness values were obtained. Experiments were conducted according to experimental conditions as given in Table 1 by varying pressure from 100 kPa to 400 kPa whereby keeping temperature constant at 25°C; and by varying temperature from 10°C to 90°C, maintaining a constant pressure of 100 kPa. After machining the specimens are again subjected to ultrasonic cleaning for 10 minutes. Subsequently, mass of the specimen, surface roughness and SEM images were obtained after machining. The results obtained are compared with the results before machining and the effect of ambient pressure and fluid temperature in cavitation erosion in discussed.

Table 1 - Experimental conditions

Experiment parameters	**Values**
Ultrasonic Frequency	20 kHz
Amplitude	70 µm
Working fluid	Deionized water
Atmospheric pressure	100; 200; 300; 400 kPa
Temperature	10; 30; 50; 70; 90°C
Working distance	1 mm
Workpiece	SAE 304 stainless steel

RESULTS AND DISCUSSION

Cavitation erosion occurs usually in several stages namely the incubation stage, acceleration stage, maximum stage, deceleration stage and the terminal stage. Hence, the specimens are subjected to cavitation erosion till the deceleration stage at various ambient pressure and fluid temperature conditions. The potential material removal mechanism and mass loss related to cavitation erosion are discussed. Variation in surface roughness due to mass loss is discussed using roughness measurements and observed SEM images.

Material removal mechanism

During USM, the horn is made to vibrate at an amplitude of 70 µm inside the liquid medium. Material removal mechanism in USM is illustrated in Figure 2.

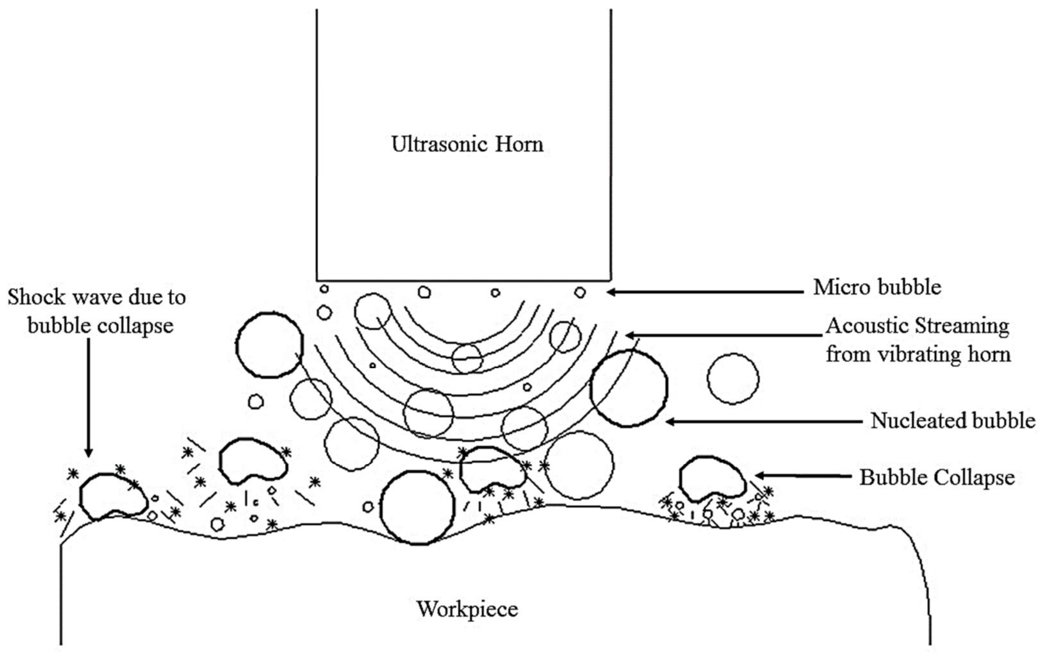


Fig. 2 - Material removal mechanism in ultrasonic machining

The vibration from the horn causes fluctuations in the static pressure of the liquid. The fluctuating pressure is high when horn moves down and low when horn moves up. When the low pressure created is well below the local vapor pressure of the liquid, cavities are formed. These cavities are referred to as cavitation bubbles. These cavitation bubbles nucleate to a certain size in the range of 0.1-1.5mm (Dular, 2013) and explode. During bubble explosion, primarily high pressure is induced at the workpiece surface; secondarily shock waves are generated. This pressure, in the range of several hundred atmospheres (Suslick, 1999) along with shock waves abducts material from the workpiece surface. These are referred to as erosion pits in cavitation erosion. It is certain that acoustic streaming occurs in the liquid due to ultrasound from the horn tip. Therefore, there is a definite possibility that acoustic streams accelerate the bubbles to collide onto the workpiece thus enhancing the material removal mechanism.

Effect of atmospheric pressure

The results shown in Figure 3 illustrates the trend of mass loss in USM with increase in ambient pressure and a constant temperature of 25°C. The mass loss during USM at 100 kPa for 25 minutes is 0.2 mg.

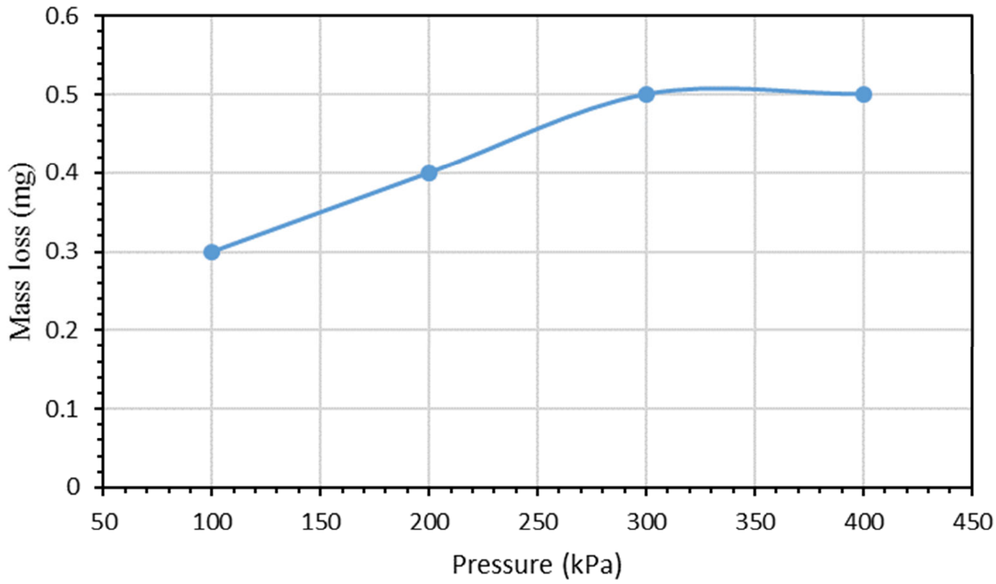


Fig. 3 - Mass loss vs ambient pressure

Mass loss increased up to 0.5 mg at 300 kPa and levelled off. Therefore, the increase in mass loss is because, vapor pressure of cavitation bubble is much lower than the atmospheric pressure. During this condition, there is no possibility of the cavitation bubbles to collapse at the water surface, since fluids always flow from high to pressure regions. Therefore, the cavitation bubbles (vapor bubbles) formed would be pushed back inside the liquid making it impossible for the bubble to explode at water surface. Thus, the cavitation bubbles formed are completely made to explode inside the liquid medium exerting high stresses and shock waves at workpiece surface. This enhances the material removal mechanism in cavitation erosion. overall, a linear increase in mass loss was observed as ambient pressure increases.

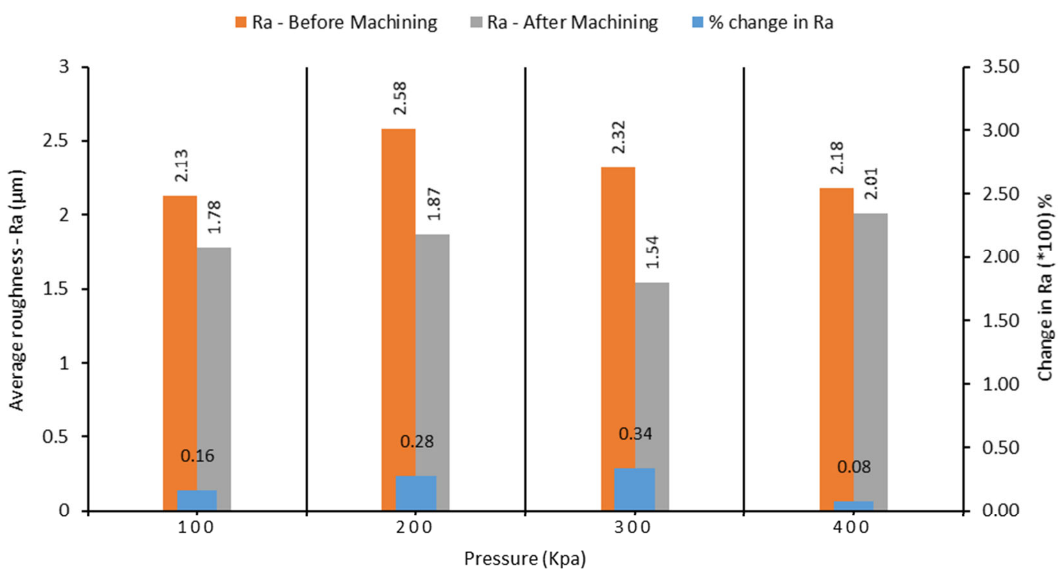
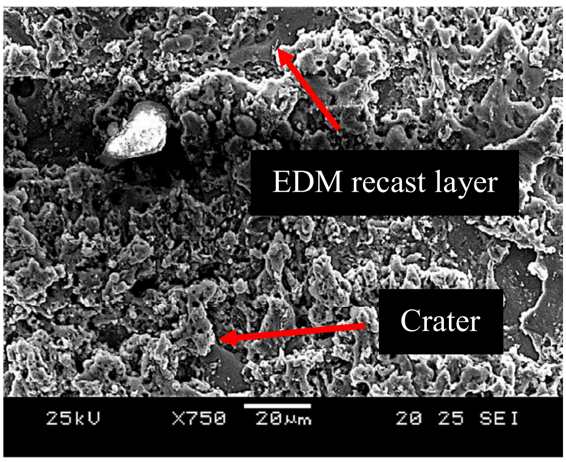


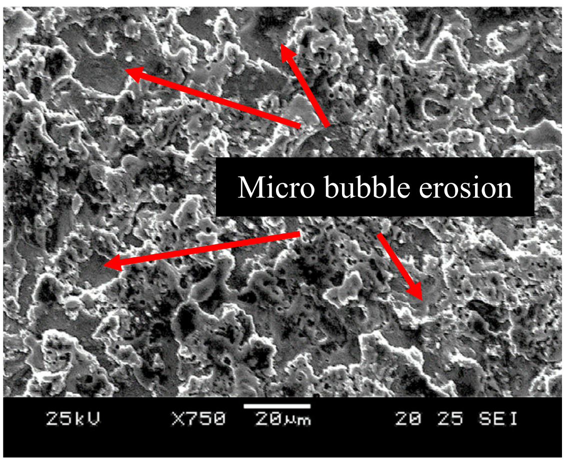
Fig. 4 - Change in surface roughness vs ambient pressure

Surface roughness values were measured and change in roughness values are shown in Fig. 4. It should be noted that this study has been primarily concerned with applying USM directly on EDM surface. Hence, polishing the workpiece surface before machining was not preferred. From the results, it is certain that cavitation erosion has improved the surface roughness. A maximum of 34% change in roughness was observed at 300 kPa. The SEM images obtained at this test condition support the results showing cavitation eroded surface, thus enhancing the surface roughness.

SEM images obtained before machining provides a clear view of the workpiece surface. Due to wire cut EDM an EDM recast layer was formed on the workpiece surface as shown in Fig. 5 (a), these recast layers also led to formation of craters as shown in Fig. 6(a) and Fig. 7(a), partially molten metal left over during EDM was also noted as shown in Fig. 7(a). These molten metals settled as bumps on the workpiece surface.

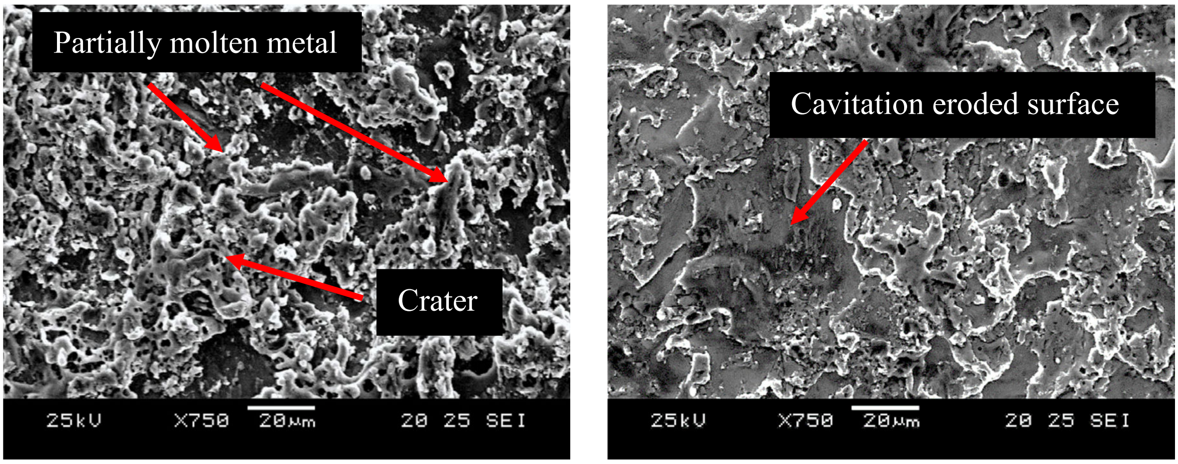


(a)



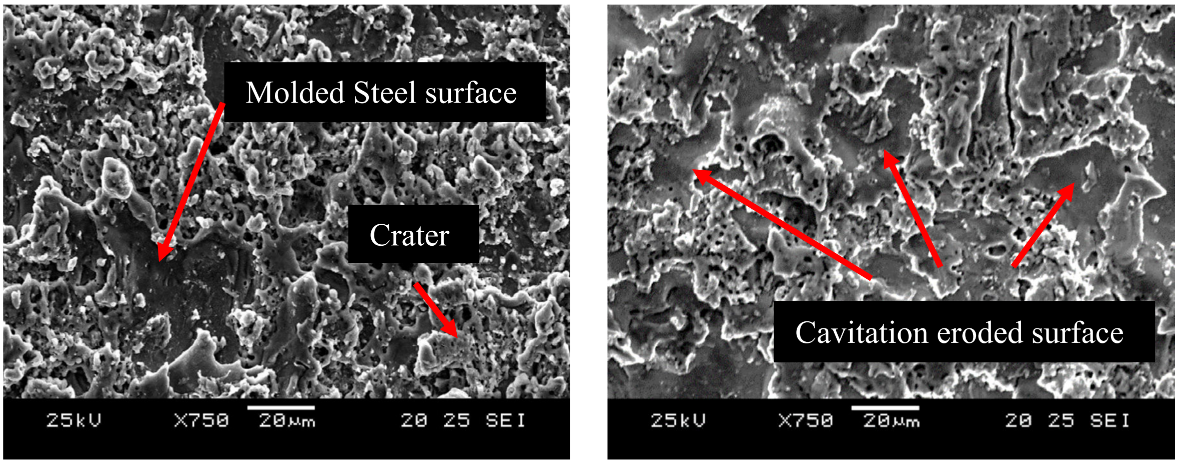
(b)

Fig. 5 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at P=100 kPa



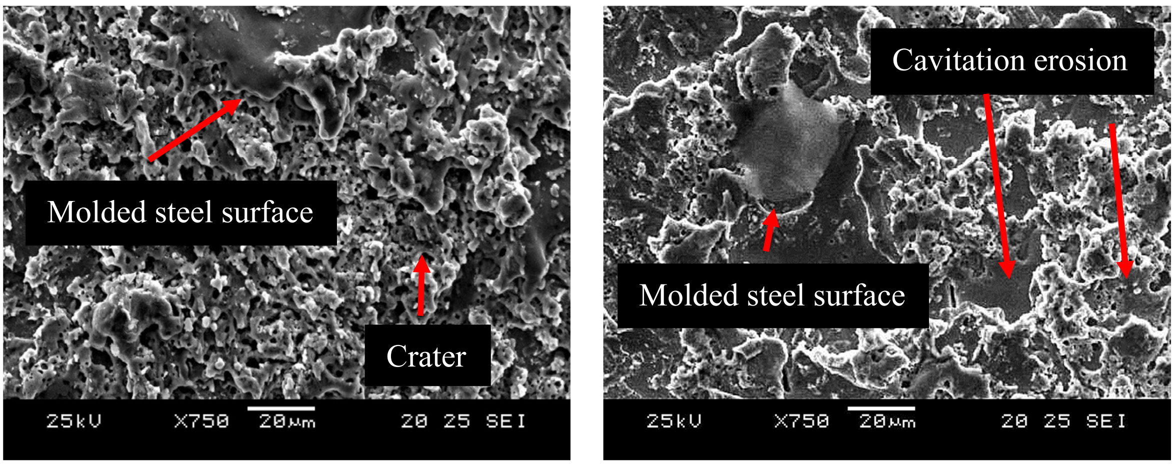
(a) (b)

Fig. 6 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at P=200 kPa



(a) (b)

Fig. 7 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at P=300 kPa



(a) (b)

Fig. 8 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at P=400 kPa

The specimen surface after EDM consisted of originally molded steel surface as shown in Fig. 7(a) and Fig. 8(a). At 300 kPa test condition SEM images showed that cavitation erosion was maximum. Hence, most of the recast layer and partially molten metal bumps were eroded. These observations support the peak mass loss obtained and a better surface roughness.

Effect of temperature

Figure 10 shows the trend of mass loss with increase in temperature of working fluid at a constant pressure of 100 kPa. Initially the temperature of the bath was lowered to 10°C and USM is carried out. At 10°c it was found that the bubble population under the horn was very less. The bubble production depends on the vapor pressure of the liquid which varies along with temperature. Lowering the temperature will result in lower vapor pressure of liquid. Therefore, at 10°C the vapor pressure of the liquid would be very low.

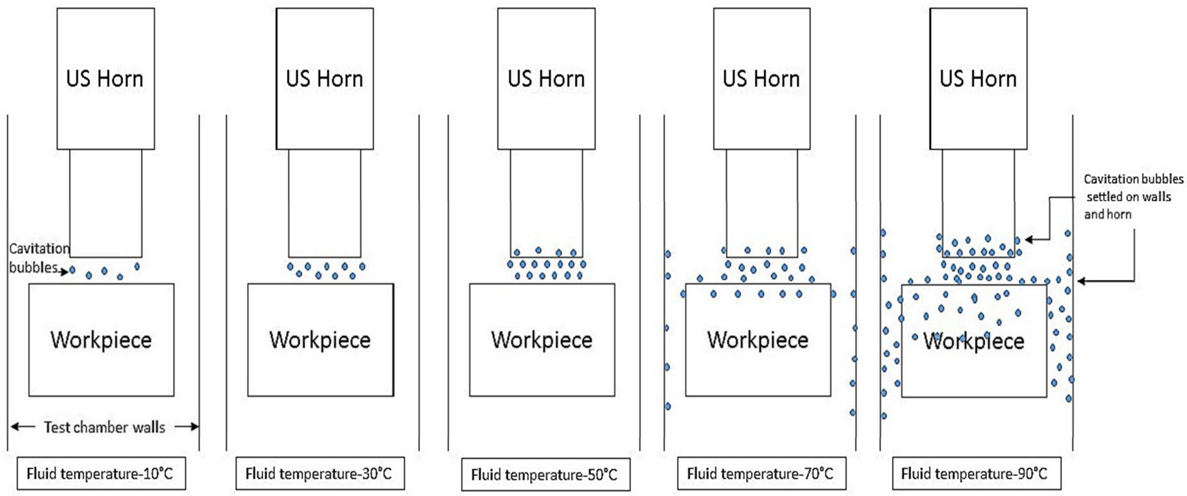


Fig. 9 - Bubble population at various fluid temperature

Hence, for a cavitation bubble to be generated, the low pressure created by the vibratory horn should be much lower than the vapor pressure of liquid. Despite, the low pressure generated from the vibratory horn at 10°C was not well below the vapor pressure of liquid. This led to very less bubble population.

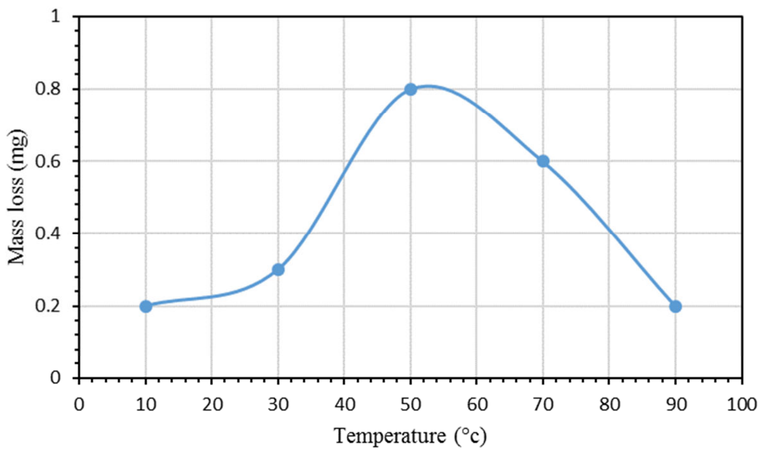


Fig. 10 - Mass loss vs fluid temperature

Hence, a mass loss of only 0.2 mg was recorded. At 30°C and 50°C high bubble population as shown in Figure 9 was observed, which in turn increased the mass loss to a peak of 0.8 mg. At 70°C and 90°C even higher bubble population was observed, but it was noted that the bubbles did not explode instead settled near the horn and on the sides of workpiece and test chamber. This is due to the insufficiency of bubbles to trap sufficient vapor inside it and explode. Hence mass loss declined from 0.8 mg to 0.6 mg and 0.2 mg respectively. In conclusion, bubble population at various temperatures affected the amount of material removal.

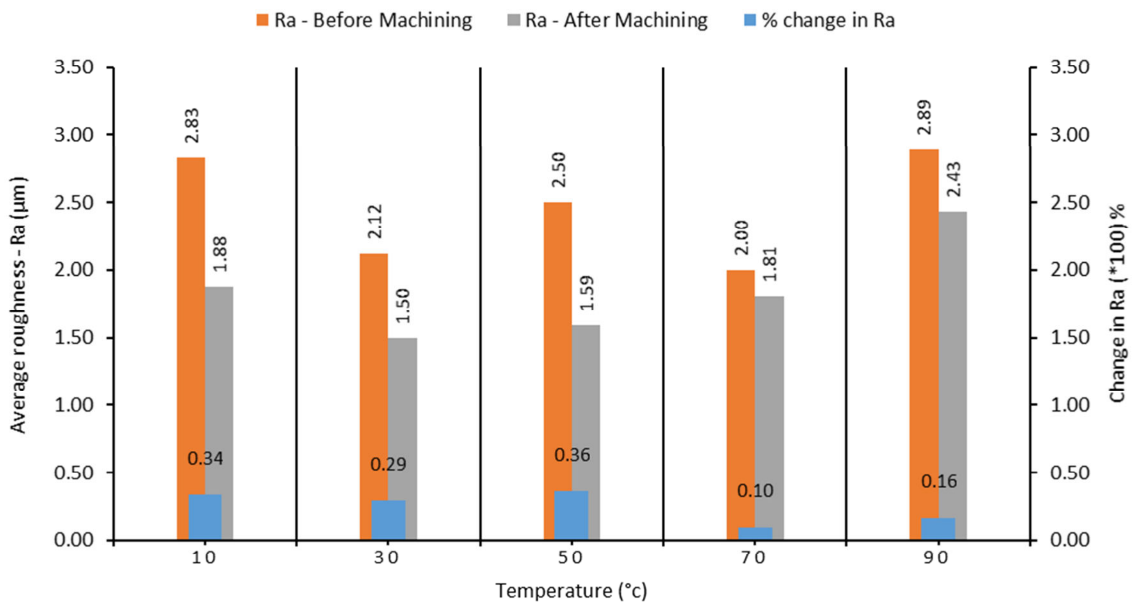
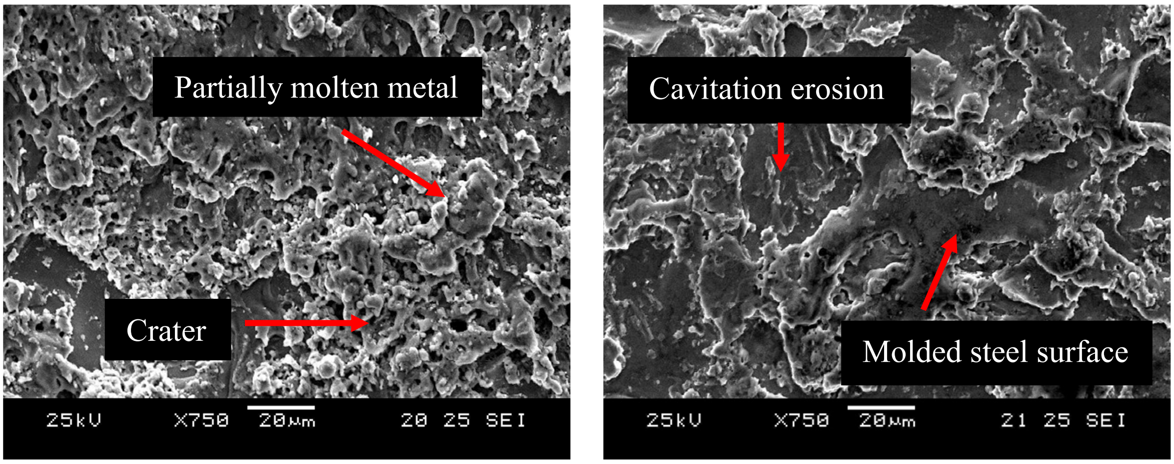


Fig. 11 - Surface roughness vs fluid temperature

After the mass loss measurements, specimens were subjected to surface roughness measurements. Change in surface roughness at various temperatures are shown in Figure 11. A 36% change in surface roughness was observed at 50°C, this supports the maximum mass loss obtained at 50°C. The maximum mass loss observed led to removal of surface irregularities and improved the roughness values at this condition.

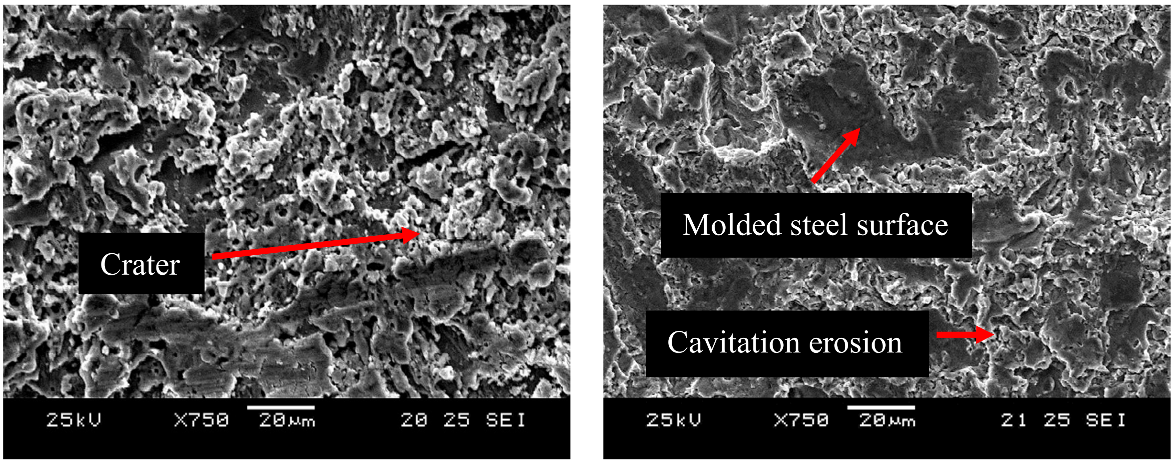
SEM images were obtained to compare the surface topography before and after USM. Erosion pits left by cavitation bubbles were clearly visible. It was also found the plastic deformation due to cavitation erosion and surface undulations were high at temperatures 30°c ,50°c and 70°c as shown in Figure 13(b), Figure 14(b) and Figure 15(b).

The surface undulations are a major result of bubble collapse at work piece surface. Initially an indentation pit was created sue to bubble collapse, further collapse of the bubbles was concentrated in the same pit causing material removal and leaving a wavy undulation in the surface. Even after machining, partially molten metals and craters remained at 90°c.



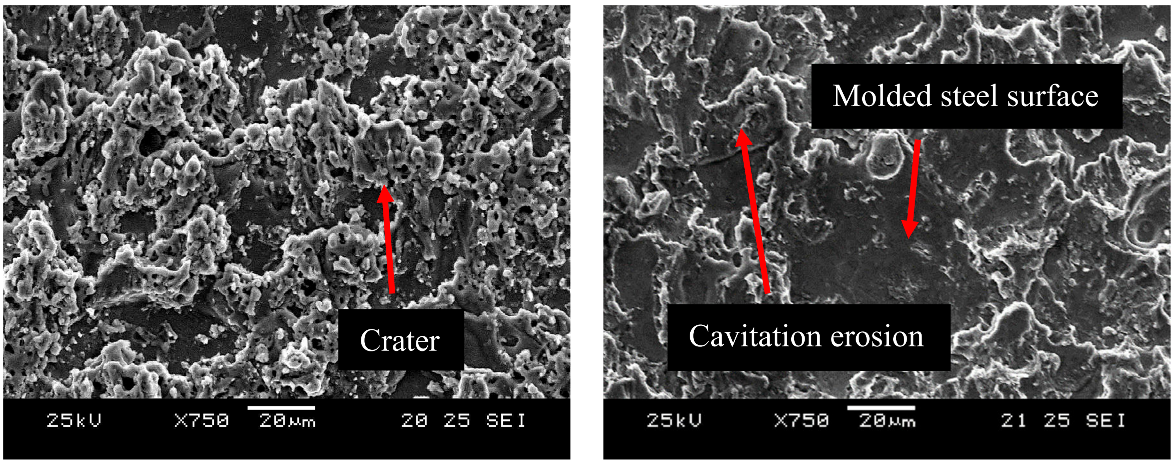
(a) (b)

Fig. 12 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at T=10^{o}c



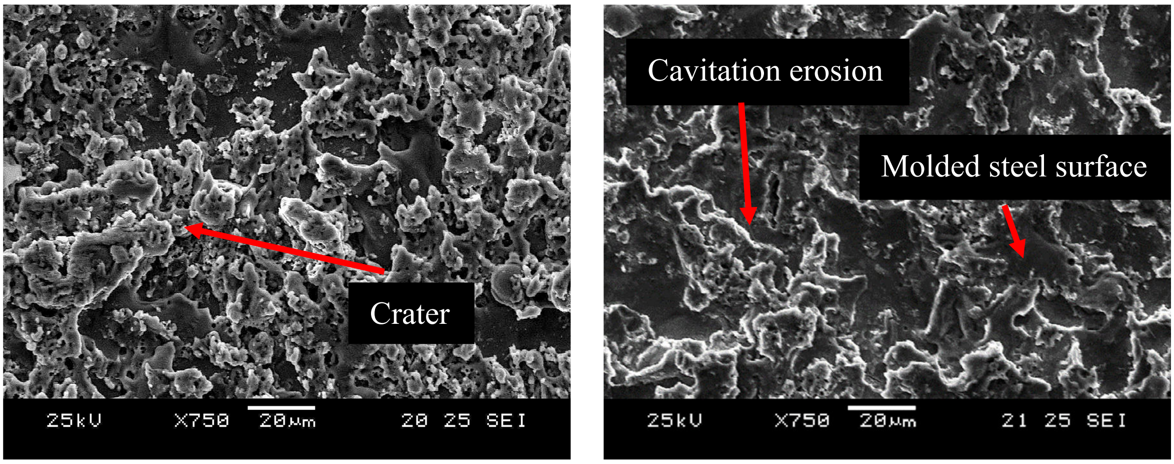
(a) (b)

Fig. 13 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at T=30^{o}c



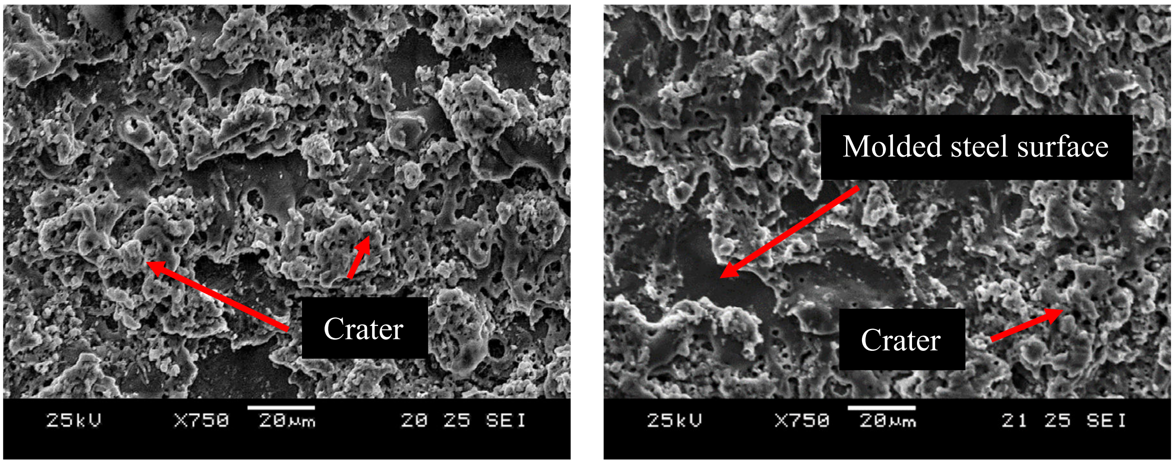
(a) (b)

Fig. 14 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at T=50^{o}c



(a) (b)

Fig. 15 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at T=70^{o}c



(a) (b)

Fig. 16 - (a) EDM cut surface of SAE 304 stainless steel (b) surface after USM at T=90^{o}c

CONCLUSION

In this study, the effect of ambient pressure and temperature on cavitation erosion in USM was studied. It was found that increasing ambient pressure and temperature during machining process enhances the material removal mechanism. The major findings from the study are listed as follows.

1) Increase in ambient pressure enhances the material removal mechanism. This is because high ambient pressure exerts a force on the vapor bubbles generated during USM. This force pushes the vapor bubbles down and makes it explode inside the liquid medium, exerting high pressure shock waves on the material surface. These high-pressure shock waves in turn erodes the material from the workpiece surface. Hence, an increase in mass loss of 0.1 mg was observed for rise in every 100 kPa ambient pressure.

2) Increasing the temperature of the working fluid enhances the material removal mechanism. It is found that the mass loss is at a peak of 0.8 mg at 50°C and gradually declined to 0.2 mg at 90°C. Hence mass loss increases with increase in temperature and declines near the boiling point of the liquid. This is because bubble explosion is higher at 50°C and decreases near the boiling point. The decrease in explosion is because of the inability of the bubbles to trap vapor inside it a grow into a larger volume and explode.

3) Major material removal mechanism in USM was found to be cavitation erosion (erosion pits due to bubble collapse) and acoustic streaming from the ultrasonic horn that accelerated the bubble to strike the workpiece surface. SEM images supported the effect of pressure and fluid temperature on cavitation erosion in USM.

Thus, controlling the ambient pressure and temperature will help in enhancing the material removal during USM. Finally, with further investigations on the effect of pressure and temperature in bubble size in cavitation help in controlling the erosion process for other application like surface finishing and surface modification.

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