Parametric Investigation on Ultrasonic Machining of Electrical Steel

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Abstract *:* Electrical steel sheets are used for the cores of motors and small transformers, and the use of such steel sheets featuring low iron loss is an effective way of reducing energy loss in motors. The laminations for magnetic cores used in such electrical appliances are manufactured by punching, mechanical cutting or cutting by laser of coils of electrical steels. The magnetic material close to the cutting edge is essentially influenced by these processes. To reach optimum magnetic properties of the material after cutting, choice of a cutting method, which does not deteriorate these properties during the cutting process is important.

Ultrasonic machining (USM) was developed primarily for machining of hard and brittle materials without imparting any deleterious effects on work material. However, it has been proved to be effective in machining hard and brittle material, range of ultrasonic machining process in terms of material to be machined is all-embracing, whether conductive or non- conductive, metallic, ceramic or composite. From literature review, number of machining parameters are identified affecting the process out of which few parameters like amplitude, pressure and plate thickness are selected as variable factors considering the feasibility of parameter variation. Material Removal Rate (MRR), Linear Tool Wear (LTW) and the Radial Overcut (ROC) is taken as response parameters. Experiments are carried out with different combination of levels of machining parameters and corresponding response characteristics are observed and analyzed. Their effect on the response parameters are also investigated electrical steel and mathematical relationship between process parameter and response is also attempt to be develope for prediction of process output.

Index Terms **– material removal rate, Ultrasonic machining, electrical steel, tool wear rate, radial over cut.**

I. Introduction

1.1 Electrical Steel

As an aspect of the worldwide trend towards energy consumption and preservation of the natural environment, the reduction of electricity consumption has become an extremely crucial matter in recent years. Effective utilization of electrical energy can be achieved by making electrical equipments work at higher efficiency i.e. low losses. Various efforts are being made to achieve this including application of appropriate materials with optimum electrical properties for various components of electrical equipment. For instance magnetic cores for the wide range of modern electrical and electronic devices require magnetic materials with many combinations of properties and characteristics. Of all the soft magnetic core materials, the most widely used are known as “electrical steels or silicon steels”.

Electrical steel is a special steel tailored to produce specific magnetic properties viz. small hysteresis area resulting in low power loss per cycle, low core loss, and high permeability. It is usually manufactured in cold-rolled strips less than 2 mm thick. These strips are cut to shape to make laminations which are stacked together to form the laminated cores of transformers, and the stator and rotor of electric motors. Laminations may be cut to their finished shape by a punch and die or, in smaller quantities, may be cut by a laser, or by wire EDM.

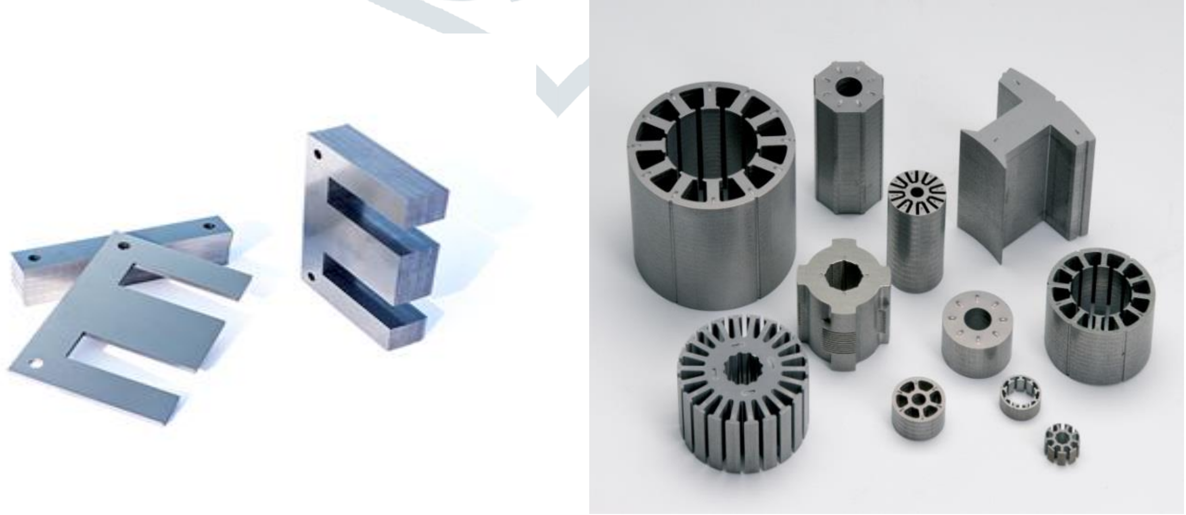


Figure 1.1: Magnetic Cores of Electrical Equipments [29]

Electrical steel is an iron alloy which may have from zero to 6.5% silicon. Commercial alloys usually have silicon content up to 3.2% (higher concentrations usually provoke brittleness during cold rolling). Silicon significantly increases the electrical resistivity of the steel, which decreases the induced eddy currents and narrows the hysteresis loop of the material, thus lowering the core loss. However, the grain structure hardens and embrittles the metal, which adversely affects the workability of the material, especially when rolling it.

1.2 Ultrasonic Machining

Ultrasonic machining is non-traditional machining process in which material is removed from the workpiece surface by the chipping action of an abrasive slurry driven by a vibrating tool at a high frequency. Range of ultrasonic machining process in terms of material to be machined is all-embracing, whether conductive or non-conductive, metallic, ceramic or composite. But it is proved to be effective when comes to material with hardness value larger than 40 HRC. In beginning of ultrasonic machining technology the first patent was granted to L. Balamuth in 1945.

USM process starts with conversion of low-frequency electrical energy into a high-frequency electrical signal, which is supplied to a transducer. This high frequency electrical energy is converted into mechanical vibrations by transducer, which are then made to transmit through horn/tool assembly. This enables the tool to vibrate along its longitudinal axis at high frequency (usually greater than 20 kHz) for supplying the mechanical means for material removal. And by designing the tool and tool holder considering their mass and form such that resonance is achieved within the frequency range capability of the machine, economical material removal rate can be obtained [17]. A controlled static load is applied to the tool and abrasive slurry (composing of a mixture of abrasive materials, such as silicon carbide, boron carbide, alumina, etc. suspended in oil or water) is pumped around the cutting zone.

1.3 Common Subunits of Ultrasonic Machining Tool and their Development

Ultrasonic machining units are supplied as cutting heads for mounting on general purpose machine tools like milling machines, or as bench units. They are also manufactured as self- contained machine tools. Regardless of their physical size or power capacity basic subunits of all the USM are same. The most important of these subunits are power supply, transducer, tool holder, and abrasive materials. These subunits are discussed in subsequent sections in terms of the research works done on them.

1.3.1 Power supply and Transducer

The power supply for an ultrasonic machine tool is more accurately characterized as a high power sine wave generator that offers the user control over both the frequency and power of the generated signal [8]. It converts low frequency (50 Hz) electrical power to high frequency (approx. 20 kHz). Transducer transforms this high frequency electrical signal into the mechanical motion in form of vibrations. The power supplied depends upon the size of transducer [16]. Dimensions of the horn and tool are adjusted mechanically to achieve resonance, in the generators of the traditionally available USM machines.

The high frequency electrical energy is then supplied to the transducers to convert electrical energy into mechanical motion. Transducers used for USM works on two different principles of operation, piezoelectric effect and magnetostriction [8].

Piezoelectric transducers are more energy efficient (90–96%). It is superior to magnetostrictive transducers in generating high vibration frequencies [8]. It is exhibits low loss and higher stability, while fragility and expensive nature weighs it down. Pierce and Vincent, working independently introduced the magnetostriction oscillator in the USM in 1928, which are better in terms if economy and robustness, with low impedance which can be easily adjusted. They are also capable of transmitting vibration over wide range of frequency band owing to its lower Q value (Q is a measure of the sharpness of the peak value of energy) [16]. But high electrical losses and low energy efficiency (about55–60%) are the main limitations of a magnetostrictive transducers.

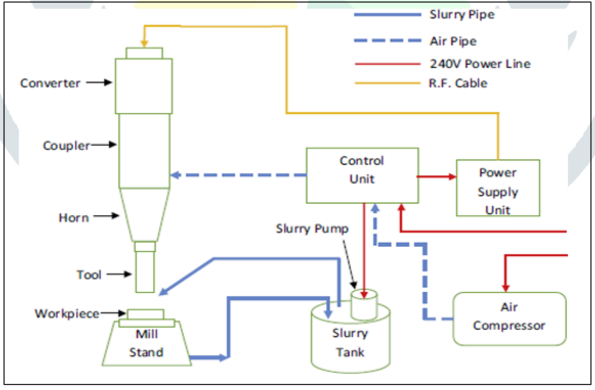


Figure 1.2: Schematic diagram of a characteristic USM setup [30]

1.3.2 The Ultrasonic Horn and Tool Assembly

The vibration amplitude at the face of the transducer is too small (0.001–0.1 mm) [3] to achieve any reasonable cutting rate, therefore, the tool is connected to transducer by means of a horn which serves as an acoustic coupler, amplification device and tool holder. For, maximum amplification, minimum energy loss and high efficiency the horn tool assembly must be designed to operate in resonance with transducer. Optimum tuning is specific for each horn material. High wear resistance, fatigue strength plus corrosion resistance are desired properties for longer tool life. Tool holders for ultrasonic machines are usually manufactured from Monel, titanium, stainless steel and aluminium bronze materials.

Amplitude of vibration at the free end (antinode) for a given frequency should be maximised with the help of efficient design. The tool material should possess all the properties that are desired for horn and in addition it should also have optimum values of toughness and hardness for the application. Tungsten carbide, silver steel, and Monel are commonly used tool materials. Polycrystalline diamond (PCD) has also been detailed for the machining of very hard workpiece material such as hot isostatically pressed silicon nitride. Tools can be attached to the horn by either soldering or brazing, screw/taper fitting. Threaded joints are preferred for the ease they offer in tool changing, but there are issues associated with them such as self- loosening, loss of acoustic power, fatigue failure.

1.3.3 Abrasives and Abrasive Slurry

In ultrasonic machining, an abrasive slurry (mixture of abrasive and fluid such as water or oil) is used to achieve the cutting action. It is supplied at the place of cutting by pumping. It is cooled for removing the generated heat to avoid undesirable cavitation effect caused by high temperature. Aluminium oxide, silicon carbide and boron carbide are the most commonly used abrasive materials. For precision machining and very hard workpiece materials, cubic boron nitride or diamond powder is also used as the abrasive. The transport medium for the abrasive should possess low viscosity with a density approaching that of the abrasive, good wetting properties and, preferably, high thermal conductivity and specific heat for efficient cooling, water meets most of these requirements.

II. Review of Literature

The review of research papers conducted in this work is presented here in four sections. The first section discusses the papers reviewed related to various processes conventionally used in machining electrical steels and their effectiveness. The second section reviews the effects of machining parameters on the response characteristics of USM. Works of researchers associated with the modes of material removal and models for predicting MRR in ultrasonic machining are explored in the next section. The fourth section discusses the conclusion and scope of the work conceived for this paper.

2.1 Electrical Steels

Electrical Steels are basically low carbon steels alloyed with 2-3% silicon which makes them magnetically superior but they are softer or delicate in nature. As the magnetic property of the steel and not the tensile strength is the important quality required and magnetic properties of electrical steels are highly affected by how they are handled when they are fabricated into cores of transformers, it is imperative that we understand the effects of fabricating procedures on them.

Stresses are of two types, elastic stress and plastic stress. An elastic stress is a temporary stress which any electrical steel may be subjected to like some load on top of the coil or a slight force to de-coil. The moment the stress is removed, the original magnetic properties of the material are restored and these are no longer damaged. However, a plastic deformation is due to winding into cores or pulling or stretching or bending electrical steels. Processing operations like slitting, shearing, notching, holing etc. also damage the grain structure of the material around the area of fabrication and working. Most of these induced stresses are plastic stresses that can only be removed by stress relief annealing. Burrs are developed during fabrication, which are unavoidable in any steel fabrication operation. Burrs decrease the stacking factor. In Indian conditions where most of the fabrication processes are performed manually and carbide blades are not used, burrs are easily developed and can dramatically increase the overall losses of the electrical steels.

Cores are manufactured by cutting steel sheets into a specified shape, then laminating and clamping the cut sheets. Punching is generally used for cutting, while laser cutting and Wire Electric Discharge Machining (WEDM) are also used in the case of small-lot production and trial manufacturing. Punching strain and thermal strain are induced by punching and laser cutting, respectively. It is well-known that cutting strain deteriorates magnetic properties. **A. Schoppa et al.**[17] experimentally studied Influence of abrasive water jet cutting on the magnetic properties of non-oriented electrical steels and compared the influence of water jet cutting on magnetic properties with that of mechanical cutting. They measured magnetic properties of strips after each cut and observed that while the mechanical cutting substantially deteriorates the magnetic properties of the material with increasing amount of the cut edge, the influence of the abrasive water jet cutting on these properties is very low and can be in case of the non-alloyed grade practically neglected. The most pronounced differences in the magnetising behaviour J vs. H between these both cutting methods were observed in the range of polarisation from 0.5 to 1.6 T. They attributed the minimal influence of this method on the magnetic properties of non-oriented electrical steel to the lower deformation of the soft magnetic material in the area of the cut edge and from the cooling effect of the water during the abrasive water jet cutting. **Yousuke Kurosaki et al.**[18] studied Importance of punching and workability in non-oriented electrical steel sheets and evaluated the effects of cutting and clamping methods on the deterioration of magnetic properties. In this study, they compared the characteristics of cut edges and the magnetic properties of non-oriented electrical steel sheets cut by shearing, laser cutting and WEDM. Figure 1.3 shows the appearance and composition of the cut edges observed by scanning electron microscope. In the case of shear cutting, roll over, sheared surface, fractured surface and burr were observed. Wave undulation on the cutting surface of laser cutting can be seen. The surface produced by WEDM cutting was porous. Figure 1.4 shows the magnetic properties of the specimens. Iron loss W15/50 of the cutting specimen with WEDM was the lowest, with shearing and laser cutting 0.2 W/kg higher. The magnetic properties of the three specimens were the same after stress relief annealing because strain was relieved.

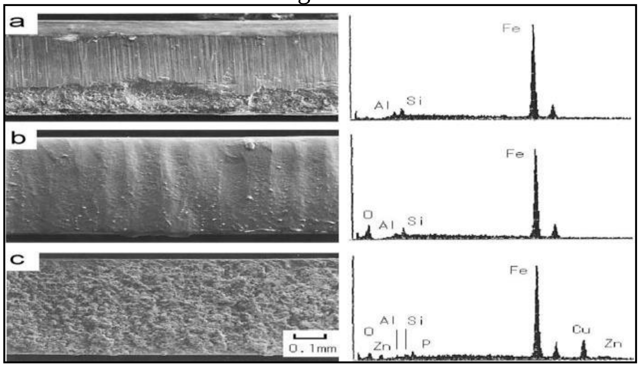


Figure 1.3: Appearance of the cut edges: (a) Shearing, (b) Laser Cutting, and (c) WEDM [18]

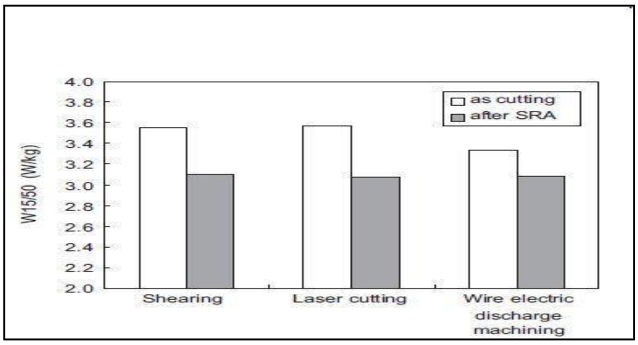


***Figure 1.4: Iron loss W15/50 of the specimen as-cutting and after stress relief annealing** [18]*

Piotr K. Klimczyk et al. [19] investigated influence of cutting techniques on magnetostriction under stress of grain-oriented electrical steel. The level of stress retained in the strip was assessed by measuring the shift of magnetostriction versus stress curves before and after annealing. Comparable shifts of stress sensitivity curves were observed for three strips cut from the same sheet using each cutting technique. Cutting techniques used here all set up compressive stress in the strips. Evidence of high compressive stress after laser cutting, was confirmed by distorted B-H loops and the creation of a surface magnetic domain stress patterns. EDM seemed to leave less or no amount of compressive stress in the cut region.

2.2 Ultrasonic Machining Process

As per discussion in previous chapters ultrasonic machining is widely used non-traditional processes; especially for hard, brittle and fragile materials although it is applicable to nearly any material, whether conductive or non-conductive, metallic, ceramic or composite. But there is ample scope for application of USM for establishing cost effective machining solutions. Performance measures in USM process are dependent on the work material properties, tool properties (hardness, impact strength and finish), abrasive properties and process settings (power input, static load, and amplitude).

2.2.1 Operating Parameters and Their Effect on Machining Characteristics

The major operating parameters affecting machining characteristics are amplitude of vibration, frequency of vibration, mean dia. of abrasive grain, volumetric concentration of abrasive particles in slurry and static feed force. Their effect on machining performance is presented in subsequent sections.

Material removal rate

G.S. Kainth[8] studied Mechanics of Material Removal in Ultrasonic Machining. They carried out an analysis considering the non-uniformity of abrasive grains to assess the relation between the removal rate and static load/amplitude. Their calculations yielded approximately a linear relation between material removal rate and static load. **M. Komaraiah and P. N. Reddy**[11] studied Relative performance of tool materials in ultrasonic machining and investigated the influence of tool material properties, i.e., hardness on the material removal rate in USM of glass. Also, the material removal rate has been found to vary in a linear proportion to the hardness of the tool being used. **T. C. Lee and C. W. Chan**[14] studied Mechanism of the ultrasonic machining of ceramic composites and reported an optimum value of amplitude beyond which the MRR obtained tends to stabilize. When a larger grit size of the abrasive is coupled with a low value of amplitude, the MRR obtained is reported to be substantially poor due to ineffective circulation of slurry under the tool. **T. B. Thoe**[15] has been reported that the machining rate is directly proportional to the tool form and shape factor. Use of hollow tools has been reported to result in higher rates of material removal than ones with solid geometry for the same area of the cross-section. **Sanjay Agrawal et al.** [23] studied the mechanism and mechanics of material removal in ultrasonic machining and established the relationship for the material removal rate for micro-brittle fracture mode, considering direct impact of abrasive grains on the workpiece, based on a simple fracture mechanics analysis. The analysis also revealed that the material removal rate increases with an increase in the size of abrasive grain, the static load applied, and the amplitude of the tool tip. However the material removal rate decreases at higher static loads because removal of debris becomes more difficult as the tool is not allowed to vibrate properly. In addition, higher loads results in a low amplitude of vibrations with increased contact time. This information leads to an important conclusion that material removal rate can be controlled by properly controlling the different parameters, thereby making the process reproducible.

Tool wear rate

Tool wear is an important variable affecting the performance of the process (machining rate and accuracy) and in combination with other factors such as tool material, abrasive type and slurry feeding methods interferes with the actual machining operation. Tool wear pattern is divide into longitudinal wear and lateral wear. Longitudinal wear is due to repeated impounding of the tool against abrasive particles. Lateral wear is due to abrasive action of the particles in the gap between the tool and the work piece. **M. Adithan et.al.** [6] Studied Parametric influence on tool wear in ultrasonic drilling and reported that the tool wear is maximum at a particular static load, which may be considered optimum for the point of view of MRR. The tool wear increases linearly with the total depth of holes drilled. As the depth of hole drilled increases, there is a reduction in the MRR and an increase in the associated tool wear. The tool wear is proportional to the cutting time and the rate of tool wear has been found to increase with time. The tool wear tends to increase when harder and coarser abrasives are used. As a consequence, harder abrasives like boron carbide cause higher tool wear compared to softer abrasives like silicon carbide for tool of the same cross-sectional area as shown in Figure 1.5.

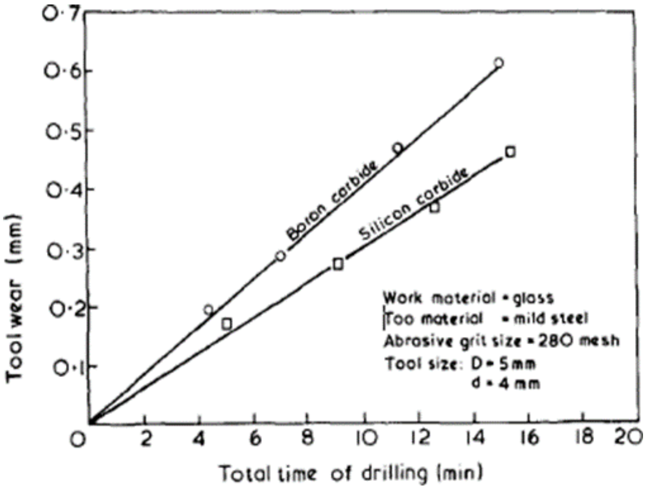


Figure 1.5: Influence of abrasive on tool wear

M. Komaraiah[11] studied Relative performance of tool materials in ultrasonic machining attempt to understand the resistance of the tool material against wear and the increase in hardness and its distribution on the tool face were also measured. They reported that for the longitudinal wear, wear rate is influence by the hardness and the impact strength of the tool material. For diametral wear, with increase in hardness of tool Material increase the wear resistance. They also states that the strain-hardening tendency varies for different tool material. They give the order of decreasing overall performance of the tool material is as follow: Nimonic-SOA> thoriated tungsten> silver steel>maraging steel > stainless steel > titanium> mild steel.

Surface finish

M. Adinath[7] studied Production accuracy of holes in ultrasonic drilling and reported that taper can be reduced by using tungsten carbide and stainless steel tools, an internal slurry delivery system and tools with negative tapering walls or fine abrasives. Taper has been eliminated by an additional lapping or by a repassing technique with continuous flow of finer abrasives with zero static loading. Higher static load and longer operating times reduce the oversize of the hole. **M. Komaraiah**[10] Investigating surface roughness and accuracy in ultrasonic machining and shows that surface roughness improves with increase in static load which reduces the abrasive size and suppresses the lateral vibrations of the tool, so minimizing the production inaccuracies in the hole drilled. It was established by them that work piece materials with higher ratio of hardness to elastic modulus involve inferior surface quality. The materials which observed higher MRR were also reported to have higher surface roughness values. **M. Komaraiah and P. N. Reddy**[11] studied Relative performance of tool materials in ultrasonic machining and compared the performance of stainless steel, titanium and niamonic-80 tools for surface finish of the glass work piece while machining with USM. Results showed that tool materials with higher wear resistance (nimonic-80) gave better surface finish as they retain their shape and finish even under the repeated impact of abrasive particles. **H.Dam et al.** [13] experimentally studied Productivity, surface quality and tolerances in ultrasonic machining of ceramics and reported that better surface finish is obtained when feed rates and depth of cut are increased. Also states that the most productive material gives the greater roughness.

Chandra Nath [20]studied Influence of the material removal mechanisms on hole integrity in ultrasonic machining of structural ceramics in which they investigated the material removal mechanism in the gap between the tool side and the hole wall for three advanced engineering ceramics, namely, silicon carbide, zirconia, and alumina. They states that both the entrance chipping and the wall integrity are due to the radial and the lateral cracks, which propagate away from the tool periphery in the radial direction. The length or size of this cracks are about 2-4 times larger than the radius of the abrasive used. At the top surface of the hole cavity, the remaining portion of these cracks appear as entrance chipping, when the damage material of the cracks get removed by the moving abrasives around the tool periphery. Under the surface, the remaining portion of the cracks appear as hole wall roughness and surface damage.

2.3 Means of Material Removal and Models

Although extensive research has been carried out to understand the mechanism of material removal and to predict the material removal rate during the process, a complete understanding is yet to be achieved. Extensive work on the mechanism of material removal has been done by Miller [2], Rozenberg et al. [4], Kumar[21] etc.

G. E. Miller[2] proposed a MRR model based on the plastic deformation restricting its application to ductile materials and show that,

- The abrasive particles are made to attack the surface of the tool tip and work piece by a pounding type Mechanism.
- Three process necessary for the machining of ductile materials are plastic deformation, work hardening and chipping. Whereas, for brittle materials only chipping is necessary.
- Plastic deformation is a linear function of stress.
- Ordinary viscosity effects in a water slurry are negligible.

L. D. Rosenberg et al[4]**.** included the statistical distribution of abrasive particle size in their computational model. They describe the complete physical picture of ultrasonic machining and shows that material is crushed only as the result of impact of the tool on abrasive particles. The volume of crushed material depends on the peak stress during the impact and on the size distribution of the abrasive particles. The rate of ultrasonic machining decreases with increased machining depth.

Jatindar Kumar[21] identified the four different mechanisms which are responsible for removal of material from the work surface. These mechanism are describe below and detailed in figure 1.6:

- Material abrasion by direct hammering of the abrasive particles against the work piece surface.
- Micro-chipping by impact of free moving particles.
- Cavitation effect from the abrasive slurry.
- Chemical action associated with the fluid employed.

The individual or combined effect of the above mechanisms result in workpiece material removal by shear, by fracture (for hard or work hardened material) and displacement of material at the surface, without removal, by plastic deformation which will occur simultaneously at the transient surface.

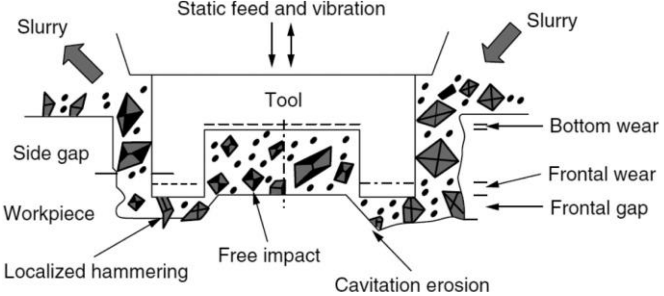


Figure 1.6: Modes of Material Removal[21]

III. Selection of parameters

3.1 Control variable

The control variables selected for the experiment therefore are,

1. Amplitude 2. Pressure 3. Electrical steel (CRGO) sheet thickness

3.2 Respponse variable

the parameters selected to be measures as representatives of the process response are,

1. Material removal rate 2. Tool wear rate 3. Radial Overcut

3.3 Level of variables

L9 orthogonal array with three levels of each for three control parameters is planned giving a total of 9 trials for drilling each as indicated in Parameter Setting Table 3.1.

The values selected for the low, medium and high level for each of the control parameters is mentioned below with suffix 1 representing low level value and suffices 2 and 3 representing medium and high level values respectively.

Table 3.1: Parameter and their Levels

Amplitude	Pressure	Thickness of CRGO Sheet
A1 = 50%	P1 = 4.0 bar	T1 = 0.23 mm
A2 = 70%	P2 = 5.0 bar	T2 = 0.27 mm
A3 = 90%	P3 = 6.0 bar	T3 = 0.30 mm

IV. Experimental results

4.1 Observation Table

The observations recorded during the ultrasonic machining of CRGO electrical steel sheet are as shown in tables below. So, here observation tables are prepared for MRR, LTW and ROC with the different value of pressure and thickness and amplitude.

4.1.1 Material Removal Rate (MRR)

Table 4.1 : Observation Table for Material Removal Rate

Sr. No.	A (µm)	p (Bar)	T (mm)	MRR (mm^3/min)
1	29.60	4	0.23	0.3316
2	29.60	5	0.27	0.5178
3	29.60	6	0.30	1.2678
4	41.44	4	0.27	0.7871
5	41.44	5	0.30	1.7989
6	41.44	6	0.23	0.9613
7	53.25	4	0.30	2.5677
8	53.25	5	0.23	1.3786
9	53.25	6	0.27	1.0193

4.1.2 Linear Tool Wear (LTW)

Table 4.2: Observation Table for Linear Tool Wear

Sr. No.	A (µm)	P (Bar)	T (mm)	LTW (mm)
1	29.60	4	0.23	0.2911
2	29.60	5	0.27	0.3133
3	29.60	6	0.30	0.3981
4	41.44	4	0.27	0.2256
5	41.44	5	0.30	0.2835
6	41.44	6	0.23	0.2001
7	53.25	4	0.30	0.1490
8	53.25	5	0.23	0.1525
9	53.25	6	0.27	0.1501

4.1.3 Radial Overcut (ROC)

. Table 4.3: Observation Table for Radial Overcut

Sr. No.	A (µm)	P (Bar)	T (mm)	ROC (mm)
1	29.60	4	0.23	0.021
2	29.60	5	0.27	0.015
3	29.60	6	0.30	0.052
4	41.44	4	0.27	0.010
5	41.44	5	0.30	0.089
6	41.44	6	0.23	0.033
7	53.25	4	0.30	0.155
8	53.25	5	0.23	0.101
9	53.25	6	0.27	0.081

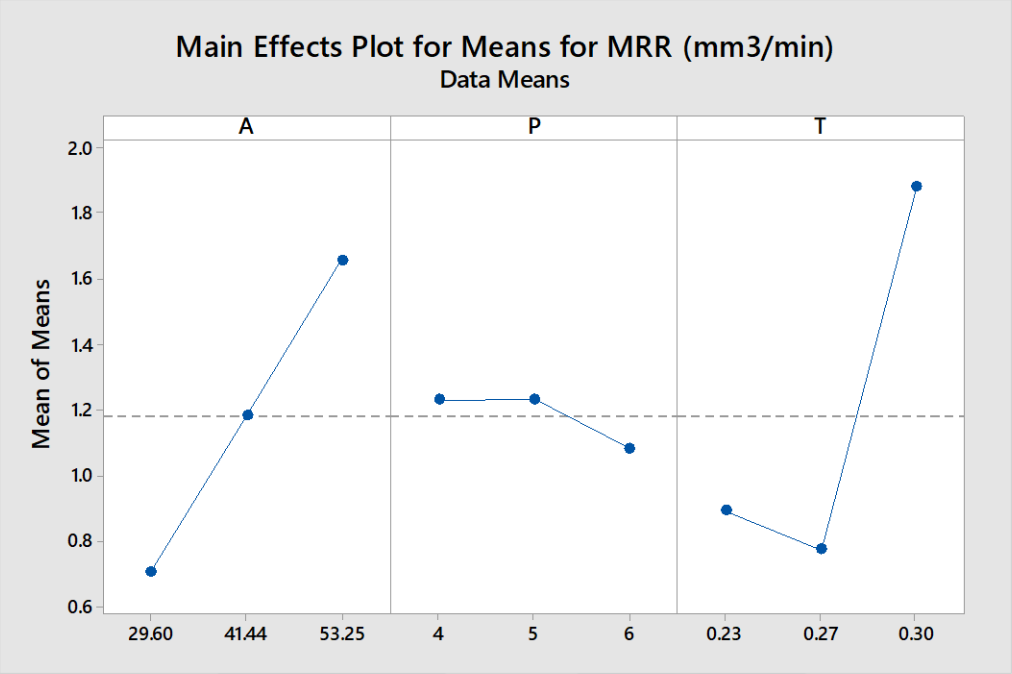
V. Result and Discussion

Analysis of variance for all the response parameters is carried out using MINITAB software for experimental data obtained during ultrasonic drilling of CRGO sheet, its result and main effect plot follows in subsequent tables and graphs.

5.1 Effect of Machining Parameters on MRR

Table 5.1: ANOVA for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A	2	1.35224	0.67612	9.65	0.094
P	2	0.04352	0.02176	0.31	0.763
T	2	2.20631	1.10316	15.74	0.060
Error	2	0.14014	0.07007		
Total	8	3.74220			

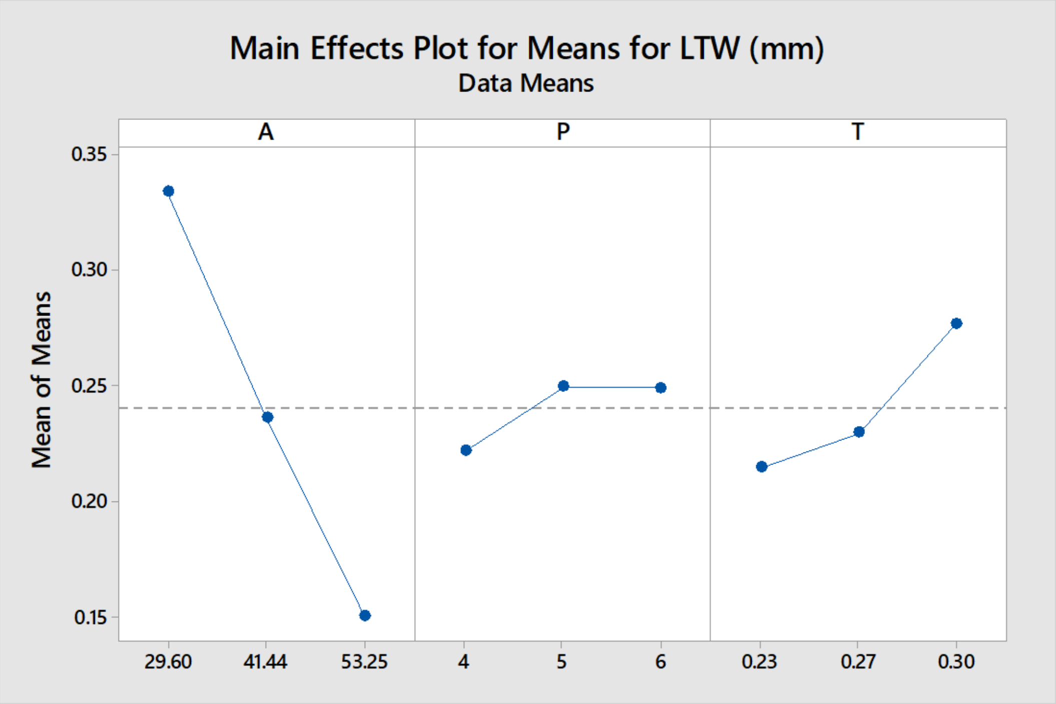


Graph 5.1: Main Effects Plot for MRR

5.2 Effect of Machining Parameters on LTW

Table 5.2: ANOVA for LTW

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A	2	0.050653	0.025326	23.40	0.041
P	2	0.001535	0.000767	0.71	0.585
T	2	0.006337	0.003169	2.93	0.255
Error	2	0.002165	0.001082		
Total	8	0.060689			

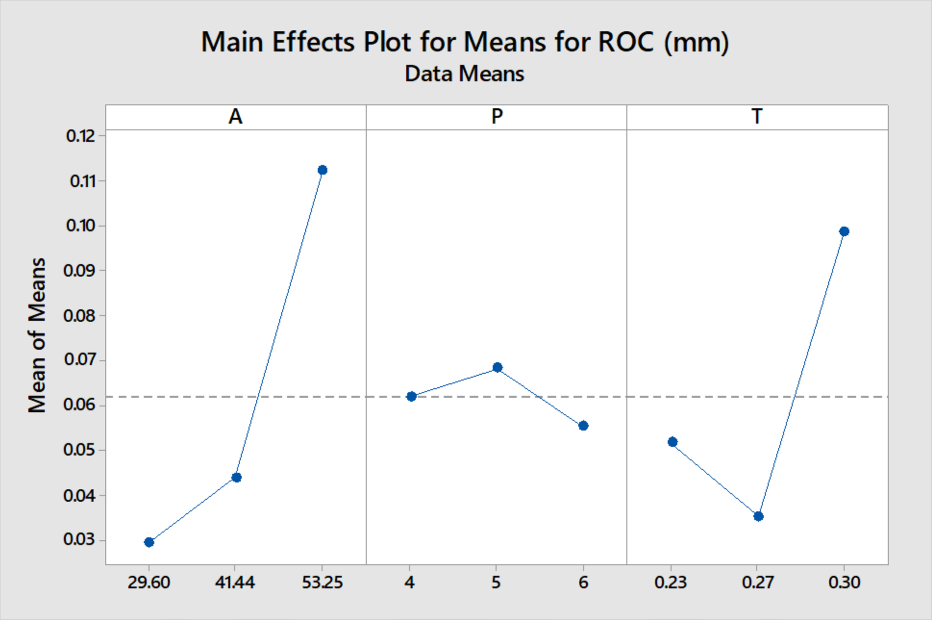


Graph 5.2: Main Effects Plot for LTW

5.3 Effect of Machining Parameters on ROC

Table 5.3: ANOVA for ROC

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A	2	0.011774	0.005887	41.92	0.023
P	2	0.000254	0.000127	0.90	0.526
T	2	0.006487	0.003243	23.09	0.042
Error	2	0.000281	0.000140		
Total	8	0.018795			



Graph 5.3: Main Effects Plot for ROC of Observation Table 2

5.4 Confirmation Test

After investigation of effect of variable parameters on response parameters like, MRR, TWL, ROC a verification test needs to be carried out in order to check the accuracy of the analysis. Form the mean effective graph generated for the observation table:2 best variable parameters was find out for each of the response parameter and for that best variable parameters three experiments has been carried out.

5.4.1 Confirmation Test for MRR

From observation table of MRR and its mean effective graph it is concluded that the condition for maximum MRR is,

Amplitude = 53.25 µm
Pressure = 4 bar
Thickness = 0.30 mm

Table 5.4: Confirmation Test Result for MRR

Sr No	A (µm)	p (Bar)	T (mm)	MRR (mm^3/min)
1	53.25	4	0.30	2.5996
2	53.25	4	0.30	2.5821
3	53.25	4	0.30	2.5502
			Average	2.5773

Here, the value of best parameter obtained from the observation table and the mean effective graph for MRR both are same. Maximum value of MRR from observation table is 2.5677 mm^3/min and from the confirmation test carried out by selecting best parameter for maximum MRR on the basis of mean effective graph is 2.5639 mm^3/min. Here, we get 0.37% of improvement in MRR.

5.4.2 Confirmation Test for LTW

From observation table of LTW and its mean effective graph it is concluded that the condition for minimum LTW is,

Amplitude = 53.25 µm
Pressure = 4 bar
Thickness = 0.23 mm

Table 5.5: Confirmation Test Result for MRR

Sr No	A (µm)	p (Bar)	T (mm)	LTW (mm)
1	53.25	4	0.23	0.1352
2	53.25	4	0.23	0.1408
3	53.25	4	0.23	0.1379
			Average	0.1379

Minimum value of LTW from observation table:2 is 0.1490 mm and from the confirmation test carried out by selecting best parameter for minimum LTW on the basis of mean effective is 0.1379 mm. Here, we get 7.45% of improvement in LTW.

5.4.3 Confirmation Test for ROC

From observation table of ROC and its mean effective graph it is concluded that the condition for Smallest ROC is,

Amplitude = 29.60 µm
Pressure = 6 bar
Thickness = 0.27 mm

Table 5.6: Confirmation Test Result for MRR

Sr No	A (µm)	p (Bar)	T (mm)	ROC (mm)
1	29.60	6	0.27	0.010
2	29.60	6	0.27	0.009
3	29.60	6	0.27	0.010
			Average	0.0096

Smallest value of ROC from observation table is 0.010 mm and from the confirmation test carried out by selecting best parameter for minimum LTW on the basis of mean effective is 0.0096 mm. Here, we get 4% of improvement in LTW.

VI. CONCLUSION

1. The MRR is found to increase with increase in amplitude and decrease with increase in pressure. MRR is observed to be showing initial decline and then increment with increase in thickness. These unconventional relations of MRR with pressure and thickness can be attributed to the delicate nature of the thin sheets of electrical steel.
2. The LTW significantly declines as the amplitude is increased whereas a little change is registered in the LTW with increase in pressure and thickness. The trends in machining time taken at the corresponding values of parameter can be held responsible for such variations in LTW.
3. The radial overcut (ROC) is found to increase with increase in amplitude, little change with change in pressure whereas it registers drop initially and then increase with increase in thickness of sheet. The bending of thinner sheets can be the reason behind such tendency of ROC.
4. Based on ANOVA results, amplitude is found to be most significantly affecting parameter for LTW and ROC whereas it is lesser significant than thickness for MRR. Thickness is found to be insignificant for LTW and significance for ROC. Pressure assumes least significance in case of all the three machining characteristics.
5. Maximum MRR is obtained for the combination of lowest pressure with maximum values of thickness and amplitude.
6. Minimum LTW is registered for the combination of maximum values of amplitude with minimum value of pressure and thickness.
7. Smallest radial overcut is observed for the set of minimum values of amplitude and middle value of thickness with maximum value of pressure.
8. On attempting mathematical modeling for MRR, it is observed that model used in current thesis are not yielding results in sync with experimental data.

VII. SCOPE FOR FUTURE WORK

Based on the work carried out and study of the literature following further investigations can be suggested

1. The parameters affecting ultrasonic machining which were not selected as control variables for this work such as abrasive types, abrasive size, slurry concentration and different tool hardness can be used to carry out further investigations to determine the effect of these parameters on the MRR, LTW and ROC.
2. Process responses like surface roughness, temperature variations in tool and work, effect of machining on magnetic properties of work material, etc. can be studied to improve the basic understanding of the energy transactions in the process.
3. Different shapes can be machined to understand the effect of machining parameters on linear and non-linear edges being cut.
4. Different shapes of tools can be designed to vary the amplitude at the tool tip.
5. Machining can be carried out with solid and conical tool tips to get the comparative idea of the process response as compared to the annular tool used in this work.
6. Mathematical models for ROC as well as LTW can be developed.
7. Models by other researchers can also be compared for the given experimental data and also those models can be updated by combining one or more of them.

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