Micro-Crack Formation of Surface Texturing using Electrical Discharge Machining On S24C Mild Steel Material with an Inclined Angle towards Biomedical Application

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Abstract. Surface texturing is a distinct identical feature of discrete dimples or grooves on a surface. In a biomedical application such as hip implant, it has been proven that these dimples can enhance the tribological properties of journal bearings. Realizing the advantages offered by Electrical Discharge Machining (EDM), it was utilized in this research to machine the dimples for the Metal-on-Metal hip implant application. In this research, three sets of inclined angles of 50°, 70°, and 90° were machined on the S24C mild steel material using EDM with pulse currents of 1A, 2A, and 3A. This research focuses on micro-crack formation along the edge of the surface of the dimple after EDM machining, which is critical in a contact sliding bearing.

1. Introduction
The hip joint is expected to be functioning well in the human body for a lifetime. It is a ball and socket joint type, which consists of the femoral head and acetabular cup that accommodates a wide range of movement while transmitting large dynamic loads that involved in many daily human life activities. It always has a risk of diseases such as osteoarthritis, rheumatoid arthritis, and trauma, which in certain conditions require these natural bearings to be replaced by an artificial one, the implant [1]. One of the materials used for hip implants is Metal-on-Metal (MoM). Over the years, many studies have been conducted to improve the tribology performance of the implant devices and prolonging its lifespan, such as by improving its material and bearing design, reducing wear by protecting the metal surface by coating, and improving its lubrication performance by surface texturing. This research’s focus is on surface texturing.

Surface texturing is a well-defined identical feature of discrete dimples or grooves on a surface. It is also known as a hole, oil-pocket, dimple, or cavity, which is a feasible method for contact performance enhancement in terms of load-carrying capacity, film thickness, friction, and wear. Various models were developed to explain the phenomena of tribology for textured surfaces. The benefits of surface texturing towards the lubrication performance were discussed by some researchers [2]. The study of the textured surfaces in hip implants has been widely conducted [3,4,6,8] and reviewed [10]. Nevertheless, it seems that an optimal texture design is difficult and still uncertain to be determined in hip implant application as the performance is highly dependent on the type of contact and the operating conditions. In addition, the manufacturing process and fabrication of the dimple is also one of the factors that can determine the role of the surface texturing approach. Figure 1 below illustrates the anatomy of the hip, hip implant and implant devices with implemented textured surface.
This research utilized Electrical Discharge Machining (EDM) technique to produce the surface texture. EDM is a non-traditional precision machining process that removes electrically conductive materials into the desired shape in terms of spark energy. It is a non-contact process in which there is no physical contact between the electrode and the workpiece. This process can eliminate mechanical stresses, chatter, and minimize vibration during the machining process, thus produces better surface finish and accuracy.

Recently, studies have been conducted in the EDM process to improve its performance, since it involved many parameters. The performance-related parameters usually measured in EDM are material removal rate (MRR), tool wear rate (TWR), machining time and surface quality [5][7]. Surface quality is determined by the surface roughness of the machined materials, the formation of white layer thickness and also the formation of crack. Most of the crack developed during the EDM process is on a micro-crack scale. Micro-crack is one of the problems that usually occurred during the machining process and has been discussed among the researchers [9,11–13].

Crack is an undesired feature that commonly occurs in engineered parts. It reduces the material ability to withstand load significantly. It usually starts small and continues to grow during operational use. During sliding between two metal surfaces, the forced contact between them can produce deformation and extension of microscopic cracks. The crack growth due to cyclic loading is called ‘fatigue crack growth,’ and the crack grows until it reaches a critical size and causing failure. Repeated cyclic loading causes crack to propagate, leading to the formation of particles, where some of them removed from the surface as wear particles. This should be avoided or at least reduced since wear is one of the main causes of implant failure [14][15].

In the study of EDM, many researchers previously investigate the effect of various parameters such as pulse current, electrode material, and type of dielectric and flushing system towards the crack formation. In this research, since the hip implant is a curvy surface, the effect of machining angle towards crack formation seems significant to being studied. Besides, to the best of knowledge, there is no research yet has been conducted to investigate the effect of machining angle to crack formation in EDM machining.

2. Methodology
This section will elaborate on the methods of the EDM and the angle setting.

2.1. EDM setting
Die-sinking EDM system for micromachining using the standard EDM circuit provided by Ben Fleming [16] is used in this research. The system as shown in Figure 2, consists of a power generator unit, the servomechanism, dielectric tank, filtering and flushing unit system. The power generator unit is used to
supply sufficient potential voltage for dielectric breakdown to occur. The servomechanism is utilized to control the distance between the electrode and the workpiece. The flushing system consists of a flushing pipe that removes the debris from the machining area. The workpiece positioning system developed previously was mounted and integrated into the system so that the angle of machining can be adjusted using a graphical user interface (GUI) [17]. Table 1 represents the EDM parameters that were used in this experiment. $I_p$, $T_{on}$, $T_{off}$, $V_{oc}$, $V_{gap}$ are the pulse current, pulse-on-time, pulse-off-time, open-circuit voltage and gap voltage respectively.

Note that electrodes were changed each time after machining a dimple to avoid the effect of tool wear and debris material that stick on the electrode hence could affect the machining performance as well as crack formation. The flushing system switched on, and the dielectric flushed onto the working area once the machining process started. During the machining process, the gap voltage and gap current were always monitored using an oscilloscope. In this research, tool wear is assumed to be negligible and the flushing flow and dielectric temperature are assumed to be constant.

![EDM machine](image)

**Figure 2 EDM machine**

**Table 1 EDM machining parameters**

| EDM parameter   | Setting          |
|-----------------|------------------|
| $I_p$           | 1 A, 2 A, 3 A    |
| $T_{on}$        | 60 µs            |
| $T_{off}$       | 30 µs            |
| $V_{oc}$        | 100 V            |
| $V_{gap}$       | 15-20 V          |
| Dielectric      | EDM oil          |
| Tool material   | Tungsten         |
| Electrode diameter | 1 mm           |

2.2. Angle setting using workpiece positioning

In this research, a special workpiece positioning system was used to machine the dimple from various angles. The cuboid flat sample of 3cmx1cmx1cm was placed and clamped on the holder and a high precision spirit level was used to make sure that the sample is correctly fixed and positioned horizontally. The GUI was then set to the required angle of machining. The definition of the machining angle and GUI setting is illustrated in Figure 3. The angles studied in this research are 90°, 70° and 50°, within the range from the previous [18]. This method provides a new contribution to the EDM study in terms of
crack formation for different angles of machining.

In EDM, due to the non-stochastic process, the time required to machine each dimple might be different, which means that the material removal rate (MRR) is usually inconsistent. This is the reason why the time parameter is not fixed in this research study. One of the most crucial parameters in this study is the depth of the dimple, where it has to be consistent during the machining process of all the dimples. Therefore, before starting machining the dimple from different angles, an equivalent depth was determined first to ensure that the same volume of material is removed. For 1mm diameter and 0.5 mm depth of a dimple, removed volume of material when the dimple is machined perpendicular (90°) using volume of cylinder formula, is 0.39 mm³. On the other hand, for the inclined angle, an equivalent volume was determined using a slanted cylinder formula. The required depth of dimple machining for the different angle is shown in Table 2. h₂ value is used to indicate the necessary depth using an indicator attached on the EDM machine.

![Figure 3 Machining angle](image)

Table 2 Equivalent depth of same volume for inclined angle of machining

| Machining angle (°) | GUI angle setting (°) | h₁ (mm) | h₂ (mm) |
|---------------------|----------------------|---------|---------|
| 90                  | 0                    | 0.5     | 0.5     |
| 70                  | 20                   | 0.318   | 0.682   |
| 50                  | 40                   | 0.081   | 0.920   |

2.3. Crack observation

The cracks were observed at each dimples on the curve surface before and after tribology testing using a tabletop scanning electron microscope, SEM, model Hitachi, TM3000. Note that all the analysis of cracks are done on the original EDMed dimple surface, where it does not undergo treatment process such as polishing or coating to avoid any alteration on the dimple structure. Before being inserted in the chamber of the microscope, the samples were cleaned using an ultrasonic machine to remove the unwanted debris or dust that will distort the crack observation. The solution used was isopropyl alcohol (IPA). The cracks were observed using the magnification range of 2000X-3000X on the top area of the dimple edge and surface.

The machining surface on the dimples consists of debris, craters, recast layers, and the lump of debris. This research study focuses on the dimple surface edges, which is the contact area between the cup and head of the implant. Therefore, the cracks formed outside of this area, such as on the wall area
inside the dimple, are ignored. The dimple area is depicted in Figure 4(a), while Figure 4(b) shows the crack images produced by SEM and the area where the crack length was measured. Image J software was used to calculate the crack length. In this research, cracks on the recast layer are also measured.

The area in which the cracks are found and measured were within the range of 25 µm from the dimple edge. Cracks with less than 0.5 µm width are considered too small and insignificant. The cracks on the dimple were divided into two, based on the location on the dimple, which is the upper and lower side, such as in Figure 4. The lower side is where the workpiece area is initially near the electrode. Most of cracks found was in micro scale. In this research, criteria of cracks are limited to cracks with more than 0.5µm in diameter in the range of 25 µm from the dimple edge. In this research, the value of circumference is important since the cracks were measured along the dimple edge. Instead of using Surface Crack Density (SCD), the circumferences were used in this research to determine the Edge Crack Density (ECD) which is defined as ratio between total crack length, \( \sum L_c \) along the dimple edge and the dimple circumference, \( C \).

\[
\text{ECD} = \frac{\sum L_c}{C}
\]

![Figure 4 Dimple area and SEM images of cracks around the dimple edges](image)

### 3. Results and Discussion

#### 3.1. Effect of Machining Time to the Crack Formation

The relationship between machining time and crack formation on the dimple edges are first investigated for 90º machining angle to machine 0.5 mm depth of dimple. Total cracks for five samples of dimples for three different current value were calculated. From the results, as shown in Figure 5, it can be summarized that the higher current will produce less ECD on the dimple edges compared to the lower current. This finding is in agreement with other researches, which has found the surface crack density
will increase when the pulse current is too low [19,20]. This is because higher current will have more material removal rate (MRR), thus required less time to complete the machining than the lower current. This will then contribute to the possibility of a reduction in crack formation. As shown in Table 3, a correlation has been made to examine the relationship between the machining time and total crack formation. It seems that machining time can influence the formation of surface crack on the ECD.

![MachiningTime and ECD vs Current](image)

**Figure 5** Machining time and ECD for current 1A, 2A and 3A

Table 3 shows the correlation between the time of machining and total crack formed on the dimple edges. Note that correlation 0 indicates the absence of a relationship between the parameters. The relationship is stronger if the correlation value is nearer to either 1 or -1. In addition, significance levels of lesser than 0.05 means it is statistically significant. N is the number of samples taken. The hypothesis made for this research is the longer the duration of the machining process, the possibility of crack formation is higher. To test this hypothesis, the total number of crack were calculated from the 90° machining angle for the three values of current. From Table 3, the Pearson’s correlation shows that the total crack formed is has a strong correlation with machining time, with the value of 0.849, and it is statistically significant with p <0.05.

| Correlations | Time | ECD |
|--------------|------|-----|
| Time         |      |     |
| Pearson Correlation | 1    | .849** |
| Sig. (2-tailed)            | .000 |
| N            | 15   | 15  |
| ECD          |      |     |
| Pearson Correlation | .849** | 1   |
| Sig. (2-tailed)            | .000 |
**Correlation is significant at the 0.01 level (2-tailed).**

### 3.2. Effect of Machining Angle to average crack length for different current setting

The average of ECD measured from 5 samples for each setting has been calculated and depicted in Figure 6. It can be seen that the angle of machining affects the ECD formed for higher current (2A and 3A). The ECD increases when the machining angle is decreased, which maybe because of the duration of the workpiece exposed to the spark is increasing. However, for 1A, the result of the crack formed is vice versa. The effect of the current is predictable when using the 90° machining angle, but it became unpredictable when the angle is 50°. Figure 6 also shows that the ECD formed is reduced when the machining angle is reduced. This is probably because the tilted workpiece surface makes it is easier to flush away the debris and reduce arcing when the debris not properly flushed away. Besides these factors, the crack formation can also be influenced by other machining conditions and parameters.

![ECD vs Machining Angle](image)

**Figure 6. ECD vs. machining angle**

From the results, it is clearly shown that the average ECD on the dimple edges depends on the pulse current. The higher the current used, the lesser the average total crack formation. However, it can be observed in Figure 7 that the total ECD is much higher at the lower side of dimple for the machining angle of 50° and 70°. This is the side where the workpiece positioned initially, which is nearer to the workpiece. This means that it has a longer exposure duration to the spark during the machining compared to the upper side.
Figure 7 ECD at each side

4. Conclusion

This research study is conducted to investigate the crack formation using the EDM technique for biomedical purposes, specifically the MoM hip implant. In this research, it shows that the higher current, 3A will produce dimples with fewer cracks along the dimple edge. It has also been found that the machining angle of 90° will give consistent and predictable results of ECD along the dimple edge compared to 70° and 50° angle. The possibility of the crack to form on an inclined angle is higher at the workpiece area because of longer exposure to the spark. This factor needs to be taken into consideration while machining the dimple for the MoM hip implant application.

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References

[1] Jln, Z.M., Medley, J.B., Dowson, D., Fluid film lubrication in artificial hip joints 2003, 237–256.
[2] Ohue, Y., Tanaka, H., Effect of Surface Texturing on Lubricating Condition under Point Contact Using Numerical Analysis. Engineering 2013, 5, 379–385.
[3] Ghosh, S., Choudhury, D., Roy, T., Bin Mamat, A., et al., Tribological investigation of diamond-like carbon coated micro-dimpled surface under bovine serum and osteoarthritis oriented synovial fluid. Sci. Technol. Adv. Mater. 2015, 16.
[4] Razak, D.M., Syahrullail, S., Sapawe, N., Azli, Y., Nuraliza, N., A new tribological approach on metal cup with optimized pits model using spark discharge machine. Part. Sci. Technol. 2016, 34, 209–216.
[5] Gnanavel, C., Saravanam, R., Chandrasekaran, M., Pugazhenthi, R., Restructured review on Electrical Discharge Machining - A state of the art. Int. Conf. Emerg. Trends Eng. Res. 2017, 183.
[6] Roy, T., Choudhury, D., Ghosh, S., Mamat, A. Bin, Pingguan-Murphy, B., Improved friction and wear performance of micro dimpled ceramic-on-ceramic interface for hip joint
arthroplasty. *Ceram. Int.* 2015, 41, 681–690.

[7] Jamwal, A., Kumar Vates, U., Aggarwal, A., Effect of electrical and non electrical parameters on the performance measures of Electro-Discharge machining: A Review 2017, 1, 925–936.

[8] Gao, L., Yang, P., Dymond, I., Fisher, J., Jin, Z., Effect of surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants. *Tribol. Int.* 2010, 43, 1851–1860.

[9] Ekmekci, B., White layer composition, heat treatment, and crack formation in electric discharge machining process. *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* 2009, 40, 70–81.

[10] Ghosh, S., Abanteriba, S., Status of surface modification techniques for artificial hip implants. *Sci. Technol. Adv. Mater.* 2016, 17, 715–735.

[11] Puthumana, G., Joshi, S.S., Characterization of micro-crack formation on machined surfaces in dry EDM using shielding Characterization of micro-crack formation on machined surfaces in dry EDM using shielding 2013.

[12] Lee, H.T., Tai, T.Y., Relationship between EDM Parameters and Surface Crack Formation. *J. Mater. Process. Technol.* 2003, 142, 676–683.

[13] Bhaumik, M., Maity, K., Effect of Electrode Materials on Different EDM Aspects of Titanium Alloy. *Silicon* 2018, 1–10.

[14] Ko, P.L., Iyer, S.S., Vaughan, H., Gadala, M., Finite element modelling of crack growth and wear particle formation in sliding contact. *Wear* 2001, 250, 1265–1278.

[15] Colic, K., Sedmak, A., Grbovic, A., Burzić, M., et al., Numerical simulation of fatigue crack growth in hip implants. *Procedia Eng.* 2016, 149, 229–235.

[16] Benjamin Fleming, Build a Pulse EDM, Fleming Publications, 2011.

[17] Kartiko, N., Azli, Y., Nor Liyana, H.S., Syahrullail, S., Razak Daud, M.D., Development of computer-aided EDM for machining micropits on spherical surface of hip implant. *Appl. Mech. Mater.* 2014, 554, 541–545.

[18] Noorazzizi, M.S., Izamshah, R., Kasim, M.S., Effects of Drill Geometry and Penetration Angle on Temperature and Holes Surfaces for Cortical Bovine Bone: An in Vitro Study. *Procedia Eng.* 2017, 184, 70–77.

[19] Lee, H.T., Hsu, F.C., Tai, T.Y., Study of surface integrity using the small area EDM process with a copper-tungsten electrode. *Mater. Sci. Eng. A* 2004, 364, 346–356.

[20] Lee, H.T., Tai, T.Y., Relationship between EDM parameters and surface crack formation. *J. Mater. Process. Technol.* 2003, 142, 676–683.