JOURNAL OF MATERIALS SCIENCE **39** (2004) 6981–6986

# Relationship between electrode size and surface cracking in the EDM machining process

H. T. LEE
*Department of Mechanical Engineering, National Cheng Kung University, 701, Tainan, Taiwan*
*E-mail: htlee@mail.ncku.edu.tw*

W. P. REHBACH
*Central Facility for Electron Microscopy, RWTH -Aachen, D-52056, Germany*

T. Y. TAI
*Department of Mechanical Engineering, Southern Taiwan University of Technology, 710, Tainan, Taiwan*

F. C. HSU
*Department of Mechanical Engineering, National Cheng Kung University, 701, Tainan, Taiwan*

This paper presents a study of the EDM machining of H13 and D2 tool steels using electrodes of different diameters. Scanning electron microscopy is employed to analyze the machined surface, and the concept of a Crack Critical Line (CCL) is introduced to explore the influence of electrode size, EDM parameters and material thermal conductivity on surface cracking. The current results reveal that the surface crack distribution is influenced by the machining parameters, the electrode diameter and the material conductivity. It is noted that cracks tend not to appear when the machining is performed with a decreased pulse current and an increased pulse-on duration. Furthermore, it is observed that changing the electrode diameter causes a parallel shift of the CCL location within the crack distribution map. The intercept of the line depends on the electrode size. When small diameter electrodes are employed in the machining process, the location of the CCL shifts upwards. This causes the no-crack zone to enlarge, and therefore permits a wider choice of machining parameters to be adopted. © *2004 Kluwer Academic Publishers*

## 1. Introduction

Electro-Discharge Machining (EDM) has found widespread application in MEMS applications, tool and mold industries and aerospace industries [1, 2]. The machining technique now plays an indispensable role in the fabrication of a wide variety of components. In the EDM process, the workpiece material is melted by a high temperature electrical discharge, and the molten material is then flushed away by a dielectric material. An ever-increasing number of new materials are being developed nowadays. Although the machining of these materials may pose difficulties for some traditional machining techniques, an inherent advantage of EDM is that its use is not constrained by the physical properties of the material being machined, and therefore it can be applied for the machining of any conducting materials, or even ceramic materials. Moreover, since the EDM process involves no direct contact between the electrode and the component during machining, no deformation of the workpiece occurs, even in the machining of thin components. Therefore, EDM is ideally suited to the machining of materials with high hardness, high strength and high toughness.

Advances in the EDM process have led to the miniaturization of the electrodes used to carry out machining. As a result, the EDM process can also be employed in the machining of micro-scale components, and consequently, EDM has now assumed a crucial role in the fabrication of MEMS components [3, 4]. However, due to the rapid heating and cooling effects induced by the machining process, a white layer tends to form on the surface of the machined component. A close inspection reveals the presence of many surface defects such as cracks on this layer. Unfortunately, removing this layer by grinding is always problematic, and especially so when the dimensions of the component are small. When the component is subjected to the impacts and stresses associated with a typical working environment, it is found that these cracks are the primary cause of component failure. Furthermore, it has been shown that the existence of surface cracks lowers the corrosion and fatigue resistance of the material [5–7]. Therefore, surface cracks are a fundamental consideration when evaluating the performance of the EDM technique, and the prime objective of EDM machining must be to establish the conditions which suppress their formation.

According to former research [8–11], crack formation can be attributed to the presence of residual stresses induced during the machining process. Bombarding the workpiece with a succession of electrical discharges causes a dramatic increase in the surface temperature, which then induces thermal stresses within the specimen. The molten material which is not removed by the dielectric material subsequently re-solidifies as a white layer upon the surface of the component. Due to the rapid cooling effect, residual stresses are induced within the white layer, and when these stresses exceed the material's ultimate tensile strength, cracking of the surface takes place. Although the phenomenon of surface cracking has been well documented in the published literature, it appears that little research effort has been directed towards establishing the machining conditions which prevent the occurrence of such cracks. Therefore, the aim of this current study is to investigate the relationship between machining conditions and surface cracking.

D2 and H13 tool steels are chosen as the specimen materials in the present investigation since they are widely used throughout mold industries. The dependence of the crack distribution upon the EDM parameters, thermal conductivity and electrode diameter is thoroughly explored, and the concept of a Crack Critical Line (CCL) is introduced to distinguish the crack zone from the no-crack region. The aim of this study is to promote a deeper understanding of surface crack formation such that this type of surface defect may be avoided in the near-mirror EDM manufacturing process.

## 2. Experimental procedure

Two CNC EDM machines manufactured by AGIE and YAWJET are used to drill 0.2 mm deep holes in the surface of D2 and H13 test materials, which have previously been quenched and then tempered twice, and which have thermal conductivity properties of 20.9 and 28 W/m°C, respectively. EDM machining of the specimens is performed using copper electrodes of various diameters, i.e., 6.4, 3.2, 1.5, 0.8 and 0.5 mm, and kerosene is chosen as the dielectric material. Previous research has shown that the quality of the machined surface is determined primarily by the pulse current and the pulse-on duration (On-time) [12]. Accordingly, the current study is based upon these two parameters, and specifies pulse currents of 4, 8, 12, 16, 24, 32 and 64 A with pulse-on times of 3, 6, 9, 12, 15, 18 and 23 $\mu$s. The pulse-off duration is equal to the pulse-on duration, i.e., the duty factor is 0.5.

After completion of the EDM machining process, the surface integrity of the sample material is examined using Scanning Electron Microscopy (SEM) at a magnification of 500 times in order to determine whether or not surface cracking is evident. When cracking is observed, the sample is classified as "crack formed".

## 3. Results

### 3.1. Surface topography

Fig. 1 illustrates the distinctive morphology of a surface which has undergone EDM machining. The electrical discharges generate an enormous amount of heat, which causes the surface metal to become molten and to vaporize. The dielectric solution sweeps away some of the molten debris, and subsequently causes the surface to undergo a rapid re-solidification process. The rapid heating and cooling effects associated with the EDM process produce the uneven fusing structures, debris globules, shallow craters, pockmarks, voids and cracks which are evident in Fig. 1. It has been shown previously that these features become more pronounced for higher values of the pulse current and pulse-on duration parameters [13, 14].

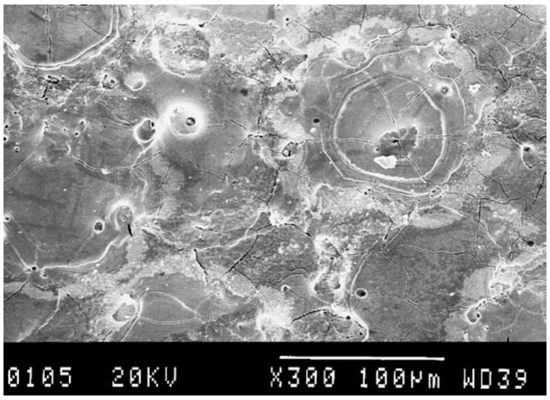


*Figure 1* Top view of the surface topography: (Material: D2; pulse current 4A, pulse-on duration15 $\mu$s).

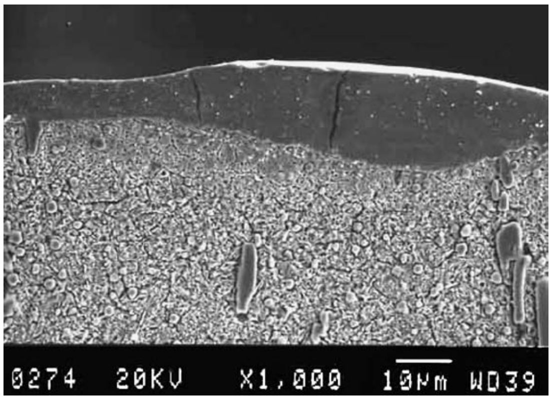


*Figure 2* Section observation of the EDMed surface: (Material: D2; pulse current 12A, pulse-on duration 15 $\mu$s).

Observation of the machined surface and the sample sections reveals that the surface cracks often tend to be micro-cracks. Fig. 2 presents an SEM observation of the section of a D2 test specimen which has undergone EDM machining. It is clearly shown that cracks are evident within the white layer, and that they originate at the machined surface and then travel perpendicularly down through the white layer towards the parent material. In the vast majority of cases, it is found that the cracks terminate within the white layer, or just on the interface of the white layer and the parent material. Only rarely do the cracks penetrate the entire white layer thickness to extend into the parent material.

### 3.2. Influence of parameters

Figs 3 and 4, respectively, present the distribution of the surface cracks in H13 and D2 tool steels for different

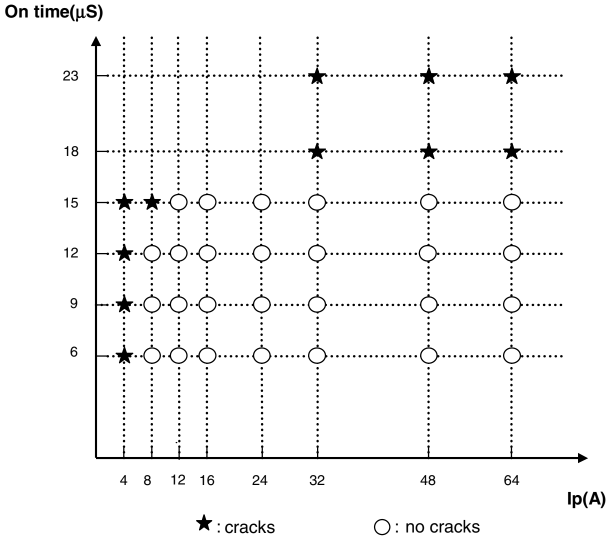


*Figure 3* Distribution of surface cracks for H13 (diameter = 6.4 mm).

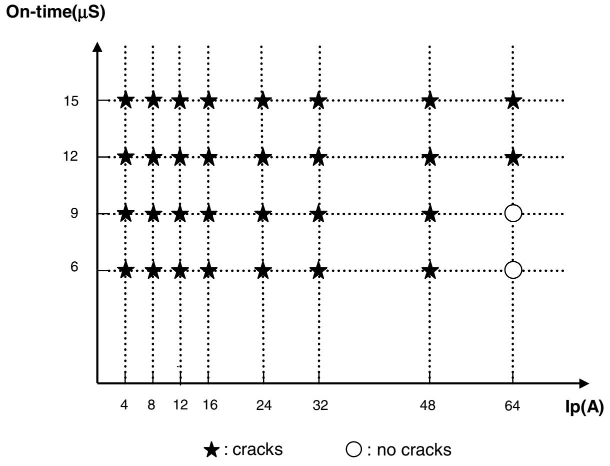


*Figure 4* Distribution of surface cracks for D2 (diameter = 6.4 mm).

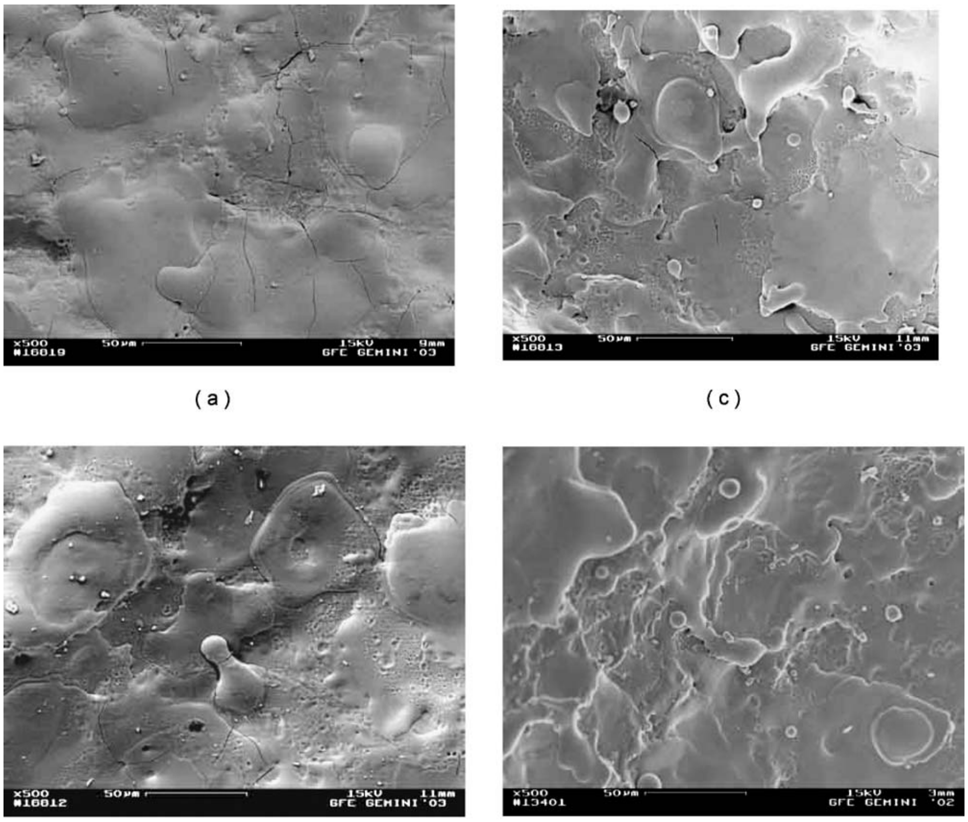
combinations of pulse current and pulse-on duration for EDM machining with a 6.4 mm diameter electrode. In an earlier study, Lee [15] observed that when the pulse current is fixed at a value between 3 and 16 A, the surface crack density increases as the pulse-on duration is increased from 6 to 16 $\mu$s. Conversely, when the pulse-on duration is fixed, the surface crack density decreases as the pulse current is increased. The results from the current study presented in Figs 3 and 4 are seen to be consistent with this observation. From Fig. 3, it is noted that when the pulse current is set at 4 A, cracks will appear in the H13 tool steel at a pulse-on duration of just 6 $\mu$s. However, at higher values of pulse current, the pulse-on duration can be increased without causing surface cracking. At pulse currents in excess of 32 A, Fig. 3 demonstrates that cracks will be formed at any value of the pulse-on duration parameter greater than 18 $\mu$s. Hence, the present results indicate that when H13 is machined with an electrode of diameter 6.4 mm, suitable values of the machining parameters, i.e., values which avoid the formation of surface cracking, are pulse currents greater than 4 A and pulse-on durations less than 18 $\mu$s. Reference to Fig. 4 shows that cracks are evident at virtually all combinations of pulse current and pulse-on duration for the EDM machining of D2 tool steel. Only when the pulse current is larger than 64 A, is a no-crack zone identified for pulse-on durations of 6 and 9 $\mu$s. Therefore, the current results suggest that a suitable combination of EDM parameters for the machining of D2 tool steel involves high pulse currents and short pulse-on durations.

The peculiar cracking tendencies of the two materials can be attributed to the difference in their thermal conductivity values. H13 has a larger thermal conductivity than D2, and is better able to transfer heat away from the surface during EDM machining. Therefore, cracks are less likely to be formed in an H13 tool steel than they are in a D2 material, which has a lower thermal conductivity [6]. In Fig. 3 (H13), it has been shown that for materials with a large thermal conductivity, cracks are more likely to be formed for small values of pulse current. Therefore, for increased pulse currents, it is possible to specify a longer pulse duration without causing the appearance of surface cracks, i.e., the no-crack zone enlarges as the pulse current increases. These conditions tend to improve the material removal rate. However it should be noted that simply increasing the pulse-on duration does not yield a continuous improvement in the machining performance. As can be seen in Fig. 3, when the pulse-on duration exceeds 18 $\mu$s, cracks will begin to form in the machined surface. Therefore, it would appear that a duration of 18 $\mu$s represents the upper limit of an acceptable pulse-on range. Regarding the low thermal conductivity material (D2), the results presented in Fig. 4 show that cracks are readily formed at most combinations of the EDM parameters, and that the no-crack zone only becomes apparent at values of pulse current in excess of 64 A. However, these machining conditions are unsuitable for precision manufacturing since an accurate EDM machining result is best achieved by applying a small pulse current for a short pulse-on duration. The present results suggest that the optimum machining performance cannot be achieved by considering only the pulse current and pulse-on duration parameters.

### 3.3. Influence of electrode size

Fig. 5a–d, respectively, show the H13 surface topographies for EDM machining with a pulse current of 6 A and a pulse-on duration of 18 $\mu$s with electrodes of diameter 4, 2, 1 and 0.5 mm. In Fig. 5a, the topography exhibits many surface cracks and a high crack density. However, as the electrode diameter is reduced to 2 mm and then to 1 mm, the degree of surface cracking lessens. As shown in Fig. 5d, when the diameter is reduced to 0.5 mm, absolutely no cracks are formed. Hence, the present results suggest that for constant values of the pulse current and pulse-on duration parameters, reducing the electrode diameter is an effective means of preventing the formation of surface cracks.

Figs 6 to 8 present the distribution of cracks evident upon the surface of the D2 tool steel when machined with electrode diameters of 3.2, 1.5 and 0.8 mm, respectively. The results confirm that the formation of surface cracks is dependent not only upon the pulse current and



(a) (c)

(b) (d)

*Figure 5* SEM photograph show that small electrode causes no cracking: (material: H13; 6 A/18 $\mu$s): (a) diameter = 4 mm, (b) diameter = 2 mm, (c) diameter = 1 mm, and (d) diameter = 0.5 mm.

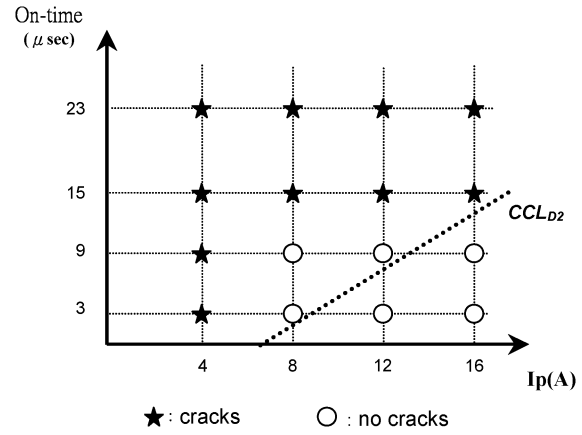


*Figure 6* Distribution of surface cracks for D2 and CCL line (diameter = 3.2 mm).

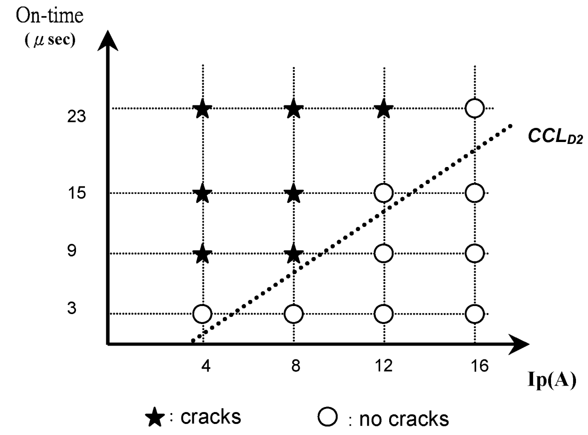


*Figure 7* Distribution of surface cracks for D2 and CCL line (diameter = 1.5 mm).

pulse-on duration, but also upon the choice of electrode diameter. The figures also introduce the concept of the Crack Critical Line (CCL), which represents the boundary between the crack zone and the no-crack zone. A combination of pulse current and pulse-on duration below this line avoids the formation of surface cracks, while those parameters which lie above the CCL will likely lead to surface cracking.

A comparison of the results presented in Figs 6–8 shows that for a constant set of EDM parameters, the location of the CCL is dependent upon the electrode diameter. It can be seen that for smaller electrode diameters, the position of the CCL within the surface crack distribution map shifts upwards, and that it shifts downwards for larger diameters. The EDM process utilizes

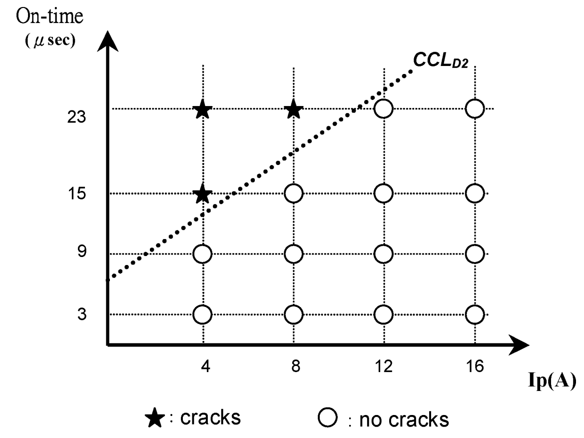


*Figure 8* Distribution of surface cracks for D2 and CCL line (diameter = 0.8 mm).

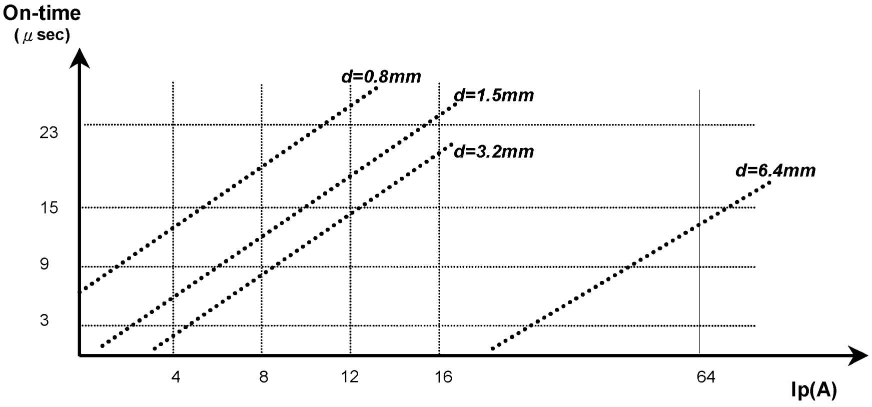


*Figure 9* Distribution of surface cracks for D2 and CCL line in different electrode diameters.

a heating effect to carry out machining, and therefore the resultant surface integrity is largely dependent upon the heat energy supplied to a unit surface area. The current results have shown that for a constant electrode diameter, increasing the pulse current tends to suppress crack formation. Furthermore, reducing the electrode size has the effect of increasing the energy density supplied to the machined surface. Since this is equivalent to increasing the pulse current, it would be expected that reducing the electrode diameter would also tend to suppress crack formation. The results presented in Fig. 5 confirm that this is indeed the case.

## 4. Discussion

Previously, Lee [15] determined that the slope of the CCL is dependent upon the material being machined, and that the slope is greater for materials with higher thermal conductivity. Although the current results presented in Fig. 9 indicate that the location of the CCL is dependent upon the electrode diameter, it can be seen that the slope of the CCL is constant, i.e., it is independent of the electrode diameter. Therefore, the factors which influence the slope and the location of the CCL are the thermal conductivity of the material and the electrode diameter, respectively.

Fig. 10 confirms that the thermal conductivity of the material changes the slope, S, of the line, while a size variation of the electrode causes a parallel shift of the line, and accordingly, changes its intercept, $A$, with the $y$-axis. Therefore, for the same size of electrode, although the thermal conductivity of D2 is less than that of H13 and more cracks are formed, a smaller size of electrode can be selected for D2 to give a similar distribution of surface cracks apparent in H13 when machining with a larger electrode.

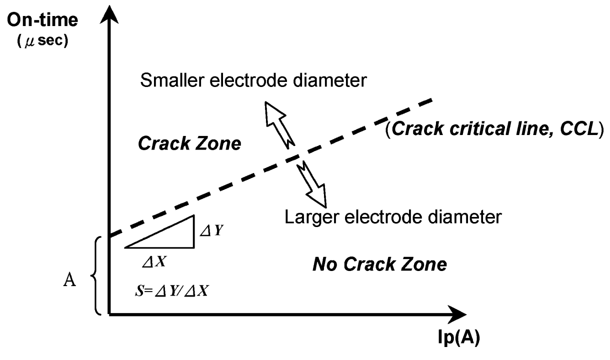


*Figure 10* Relationship of CCL between material and electrode diameter.

The current results demonstrate that an appropriate choice of electrode diameter and EDM parameters is effective in preventing crack formation. For the machining of a higher thermal conductivity material such as H13, it is possible to employ a larger diameter electrode, and to choose from a wider range of EDM parameter values. However, when a material of small thermal conductivity such as D2 is machined, crack formation is most effectively suppressed by employing a small diameter electrode, and by avoiding small pulse current values or excessive pulse-on durations.

## 5. Conclusion

This study has investigated the influence of EDM parameters, material thermal conductivity and electrode diameter upon the surface crack distribution of an EDMed surface. The main conclusions of this investigation are as follows:

1. The adoption of larger pulse currents and smaller pulse-on durations is effective in suppressing the formation of surface cracks.
2. Within the no-crack region, an increased pulse current allows a longer pulse-on duration to be applied, which results in an improved material removal rate.
3. The Crack Critical Line will be parallel shifted by variation of the size of electrode. The intercept of the line is relative to the size of electrode. The value of the intercept will become positive for smaller electrode.
4. Reducing the electrode diameter causes an upward shifting of the CCL within the crack distribution map. This enlarges the no-crack region, thus providing a greater choice of EDM parameter values which will suppress surface cracking. Conversely, increasing the electrode diameter decreases the no-crack region, and limits the choice of suitable EDM parameters.
5. When using the EDM process to machine high thermal conductivity materials, a large diameter electrode should be used in order to suppress surface cracking. However, when machining a low thermal

conductivity material, surface cracking is best avoided by selecting a small electrode, and then machining with a large pulse current and a short pulse-on duration.

## Acknowledgments

The authors wish to thank the financial support provided to this study by the National Science Council of Taiwan under Program NSC90-2216-E-006-057.

## References

1. O. A. ABU ZEID, *J. Mater. Process. Technol.* **68** (1997) 27.
2. T. MASUZAWA, K. OKAJIMA, T. TAGUCHI and M. FUJINO, *CIRP Ann.* **51** (2002) 355.
3. D. M. ALLEN and A. LECHEHEB, *J. Mater. Process. Technol.* **58** (1996) 53.
4. B. H. YAN, A. C. WANG, C. Y. HUANG and F. Y. HUANG, *Int. J. Mach. Tools Manuf.* **42** (2002) 1105.
5. L. C. LEE, L. C. LIM, V. NARAYANAN and V. C. VENKATESH, *ibid.* **28** (1988) 359.
6. L. C. LIM, L. C. LEE, Y. S. WONG and H. H. LU, *Mater. Sci. Technol.* **7** (1991) 239.
7. P. F. THOMSON, *ibid.* **5** (1989) 1153.
8. Y. FUKUZAWA, Y. KOJIMA, T, TANI, E. SEKIGUTI and N. MOHRI, *Mater. Manuf. Process.* **10** (1995) 195.
9. K. SCHMIDT and U. BUSACK, *Der Stahlformenbauer* **1** (1994) 75.
10. K. SCHMIDT and U. BUSACK, *Der Stahlformenbauer* **3** (1994) 36.
11. W.-I. JUTZLER, in “Funkenerosives Senken-Verfahreneinflu-esse auf die break Oberflaechenbeschaffenheit und die Festigkeit des Werkstuecks” (Dissertation in RWTH Aachen, 1982) 35.
12. H. T. LEE, F. C. HSU and T. Y. TAI, *Mater. Sci. Eng. A Struct. Mater* **364** (2004) 346.
13. W. J. TOMLINSON and J. R. ADKIN, *Surf. Eng.* **8** (1992) 283.
14. J. C. REBELO, A. MORAO DIAS, D. KREMER and J. L. LEBRUN, *J. Mater. Process. Technol.* **84** (1998) 90.
15. H. T. LEE and T. Y. TAI, *ibid.* **142** (2003) 676.

*Received 9 October 2003*
*and accepted 19 July 2004*