論文の内容の要旨

Fundamental research with respect to thermal phenomena of micro EDM

（微細放電加工の熱現象に関する基礎研究）

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Electrical discharge machining (EDM) is a material removal process by means of thermal erosion which utilizes electrical energy as the main source. EDM is capable of producing intricate shapes on any electrically conductive material regardless of hardness. It is widely used in tool and die making. However, current development of high speed machining which is capable of producing tool and die faster than EDM, is making the process less popular in this industry. On the other hand, increasing demands on micro components serve to increase the applications of EDM for micro machining. Currently, the demands on further miniaturization of micro components are beyond the capability of conventional EDM. Therefore, EDM process that ignites comparatively lower discharge energy than the conventional EDM has been developed. In this work, for convenience the conventional EDM process that ignites high discharge energy is called macro EDM, and the EDM process with lower discharge energy that is more suitable for micro machining is called micro EDM.

In principle, micro and macro EDM are the same, and there is no difference in the mechanism of material removal between both processes. However, micro EDM is capable of producing higher accuracy components compared to macro EDM because of the significantly small unit removal (at least 100 times smaller than that of macro EDM), and using higher precision machine tools compared to the macro EDM. The problem is, unlike macro EDM there is no comprehensive information on the energy input during micro EDM discharging for further analyses of the process. Therefore, in this work the main objective is to understand the fundamental of micro EDM with respect to the thermal phenomena of the process.

In the first chapter, the principle and mechanism of EDM were explained in general. Then, the differences of several parameters and performances between micro and macro EDM were discussed. Many researchers have compared micro and macro EDM performances with respect to the discharge energy. However, power density at workpiece is more suitable to represent the energy input during discharging. Therefore, how the power density at micro and macro EDM workpiece influences their energy and removal efficiencies was studied. In addition, these efficiencies explain the formation of white layer within the discharge crater, and the white layer directly influences the formation of residual stress near the crater.

In order to show the importance of the obtained results in this work, an example application of the results was discussed. For instance, thermal stress and structural analyses were used to understand the deformation of micro fin due to micro EDM. A heat conduction model within the EDM workpiece was built for the thermal stress analysis. Here an accurate model of the heat input which is represented by power density at workpiece is required. To determine the power density, energy distribution ratio into the workpiece (X) and plasma diameter (d) are required.

In the second chapter, the energy distribution ratio into micro EDM workpiece was determined. The discharge energy is the product of discharge current (i_e), discharge voltage (u_e) and discharge duration (t_e). These parameters are measurable using an oscilloscope during discharging. In EDM, the discharge energy is distributed into tool electrode, workpiece and the gap between them, and the amount of energy distributed into each part is different. Consequently, the ratios of energy distributed into electrodes and their gap with respect to the discharge energy are different each other.

Energy that is distributed into the tool electrode and the workpiece is then consumed for material removal, lost due to heat conduction, and lost due to convection and radiation. However, energy lost due to convection and radiation is negligibly small. Therefore, in this work X is the summation of ratio of energy consumed for material removal (X_{deb}) and ratio of energy loss due to heat conduction (X_{con}), with respect to the discharge energy.

In this work, X_{con} was determined by comparing the measured and calculated temperature rise on the workpiece due to micro EDM multiple discharges. On the other hand, X_{deb} was determined by dividing the amount of energy consumed during material removal by the discharge energy. Total removal volume per pulse can be determined experimentally. However, the main problem is that material removal in EDM is by both vaporization and melting actions, and their amounts are unknown. Furthermore, only a fraction of the molten area due to discharge is removed from the workpiece surface.

Here, to reduce the unknown to be obtained, ratio of removal by vaporization with respect to the total removal volume per pulse, g was introduced, thereby the ratio of removal by melting is equal to 1-g. Here g is between 0 and 1, where g equal to 0 and 1 means that material removal is 100% by melting and by vaporization, respectively. Consequently, in the second chapter only

X in the function of g could be determined based on the fact that X is the summation of X_{con} and X_{deb}, where X_{con} is a fixed value which was also obtained in this work, and X_{deb} is expressed by the function of g.

In the third chapter, the main idea is to determine g so that X could be obtained and then used to calculate the power density at workpiece. Here, removal mechanism analysis should be conducted to obtain the amount of removal by melting and by vaporization. However, another unknown which is required during the calculation is the plasma diameter, d. In macro EDM, plasma has been observed using high speed camera with 1 million frames per second, and spectroscopic analysis has been used to estimate d. However, the discharge gap in micro EDM is in the order of 1 μm, the discharge duration is 200 ns at longest, and the discharge energy is 1000 times lower than that of macro EDM. Thus, observation and measurement of d using the tools and methods which were used in macro EDM are not applicable to micro EDM.

Therefore, in this work a different method so-called removal mechanism analysis was used. In principle, the results of iterative calculations based on physical models which are developed using numerical method were used to be compared with experimental results. Finally, several important results of thermal phenomena of micro EDM were obtained based on the removal mechanism analysis including ratio and volume of removal by vaporization and melting, molten area volume during discharging, energy distribution ratio into workpiece, *r*atio of energy consumed for material removal, plasma diameter and power density at workpiece. Some of these results were compared with those of macro EDM. Then, how they influence removal and energy efficiencies in micro and macro EDM was discussed. Besides, from the obtained results, the accurate model of power density at workpiece could be developed for further analyses on the process.

In the forth chapter, the results in Chapter 3 were used to determine the residual stress due to micro EDM single discharge. Basically, while the white layer due to discharge is in the molten state, there is no formation of residual stress because of the free movement of elements within the layer. After solidified, the cooling process begins. Tensile residual stress is generated in this layer, resulting in contraction near the crater. To calculate the residual stress, a heat conduction model was developed considering temperature dependent thermophysical properties, temperature dependent structural properties, and material removal. The model was developed using a finite element method software. The multiphysics analysis namely structural-thermal analysis was used to calculate the temperature distribution within the workpiece due to the single discharge, and then the residual stress was obtained based on the temperature distribution result. It was found that, the distribution of residual stress in the workpiece depth direction is similar to that of macro EDM, except that the penetration depth and magnitude are lower. Then, the result was used in the structural analysis to understand the deformation of micro fin due to micro EDM.

In the fifth chapter, how thermal stress influences the deformation of micro fin which was machined by micro EDM was studied. It was found that, micro fin which was machined by micro EDM elastically and plastically deformed under certain sizes and geometry. The deformation may be caused by residual stress due to bulk material processing such as wire drawing that exists prior to the micro EDM. Since the main idea was to study the effect of thermal stress due to EDM, the workpiece first undergone the stress-released treatment before machining using EDM. It was found that all the workpieces bend toward the machining surface, indicating that the cooling process of white layer causes the formation of tensile stress near the crater. It was also found that the workpiece started to bend when its thickness was below 30 μm. Furthermore, the degree of bending was regardless of machining orientations.

To understand the deformation, wire electro-discharge grinding (WEDG) was used to produce micro fin with consistent thickness along its length. In actual machining, thousands of discharges are ignited during micro fin machining at random locations, and the residual stress distribution due to each discharge is axisymmetrical with respect to the discharge spot. Therefore, to apply the stress distribution to the machined surface randomly, three-dimensional analysis is required. Moreover, linear superimposition of the stress distribution due to single discharge does not give the stress field as a result of consecutive discharges because the stress distribution caused by a single discharge is released by melting, softening and removing of the material due to the subsequent discharges. Furthermore, change in phase and microstructure may also occur. However, three-dimensional and time-dependent simulation by imposing the thermal stress due to sequential discharges is very complicated and time-consuming. Hence, considering the purpose of the present example, for simplicity, it was assumed that the residual stress is two-dimensional, and the residual stress due to micro EDM single discharge was applied to the micro fin model uniformly along its length. It was found that the calculated deflection of micro fin was smaller than the measurement. To obtain more accurate result, the stress field due to consecutive discharges was considered, and the calculation result indicates that the deformation of micro fin in this example was due to the consecutive discharges.

Besides, the curvature of simulated micro fin was similar to the machined fin. The curvature was not uniform along the fin length. To understand the deformation, additional models with uniform rectangular beam were built. Stress distributed linearly in fin thickness direction and symmetrical about the boundary between tensile and compressive region, and stress due to single discharge were imposed within the uniform rectangular beam with simple beam support and fixed at one end support. It was found that, the non-uniform distribution of residual stress in the fin thickness direction due to discharge is the main reason to cause the non-uniform curvature of micro fin along its length.