Analysis of inaccuracies in electrochemical sizing of holes

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This paper presents a simulation based analysis of inaccuracies in the electrochemical hole sizing process. The objective is to investigate the effect of errors in process setup on inaccuracy of holes produced by the process. Setup errors include, concentricity, alignment, and roundness errors of the tool. Inaccuracy parameters of the hole are represented by roundness error of hole profile, and straightness error of hole walls. Simulations were run for different values of setup errors. Simulation results showed that tool eccentricity and misalignment result in a predetermined distortion in hole profile. The distortion is directly proportional to values of these errors. Simulation results, also, showed that the roundness error of hole profile is proportional to the tool roundness error. However, tool roundness error is imprinted at a smaller scale on the hole profile, thus implying inherent advantage of the process. Moreover, simulation results showed that the setup misalignment results in a non-uniform straightness error of hole walls.

تقدم هذه الورقة البحثية تحليل لعدم الدقة عند ضبط الثقوب بالقطع الكهروكيميائي عن طريق المحاكاة بالحاسب الآلي . الهدف هو دراسة تأثير الأخطاء في الاداه و النموذج المستخدمين لإجراء عملية التشغيل على دقة الثقوب الناتجة . تشمل عيوب النموذج انحراف المركز وانحراف المحور. عيوب الاداه مثلت بالخطأ في دائرية أداة القطع . تشمل عيوب الثقوب الأخطاء في الدائرية والأخطاء في استواء الجوانب . وقد تم محاكاة عدة قيم للأخطاء المذكورة أعلاه أظهرت نتائج المحاكاة أن انحراف المركز وانحراف المحور يؤدي إلى تشوه في مقطع الثقب ويتناسب هذا التشوه مع قيم الأخطاء المسببة له بصورة خطية أظهرت نتائج المحاكاة أيضا أن عدم دائرية أداة القطع تنتقل إلى الثقب بصورة مصغرة وتتناسب قيمتها مع القيمة المتوسطة للخطاء في الثقب بصورة خطية . بينت نتائج المحاكاة أن انحراف المحور يؤدي إلى عدم استواء جوانب الثقب بصورة غير متجانسة .

Keywords: Electrochemical, Setup errors, Simulation, Hole sizing

1. Introduction

Electrochemical Machining has been gaining interest in the past few decades due to its many advantages. Minimum tool wear, stress free machined surfaces, no-heat affected zone and high material removal rates are among these advantages. The applications of electrochemical machining extend to include auto-body dies, turbine blades and space shuttle components. Also, among the important applications of electrochemical machining is electrochemical sizing of holes, which is essential for many industries, specially, the aerospace industry. As a result considerable research work has been devoted to the simulation and control of electrochemical hole sizing process to improve its characteristics, particularly accuracy.

S. Sharma et al. [1] investigated the electrochemical drilling of holes in Inconel super alloys using sodium chloride electrolyte. They created a hole in a multilayered work part by feeding an electrode tool towards it. They measured the hole diameter and hole roundness error at each layer as a measure of hole accuracy. They reported inconsistent variations in hole diameters. They reduced this inconsistency, together with roundness errors of the produced hole sections, to process parameters. They did not consider the possible effects of errors in the motion of the tool.

M. Zybura et al. [2] studied the effect of electrode waviness and roughness and electrode feed speed on the waviness and roughness of electrochemically machined holes. They used an electrode tool produced by milling and a smooth electrode tool used previously for electro-discharge machining. Their experiments showed that increasing the feed speed of the electrode tool and reducing its roughness would improve surface characteristics of the machined hole. They also pointed that possible adjustments of machining parameters would reduce waviness and roughness of machined holes.

K. P. Rajukar et al. [3] attempted to reduce or eliminate the effect of flow field variations on machining accuracy for electrochemical drilling of holes. They applied an orbital motion to the electrode tool in addition to the feed motion. They reported improvement in process uniformity and accuracy in addition to improvement in process stability. Also, H. El-Hofy et al. [4] investigated the orbital electrochemical finishing of holes using stationary tool. They studied experimentally the effect of electrode tool diameter and orbital speed on the roundness error of the machined hole. They concluded that increasing the orbital speed for small tool diameters would reduce roundness error. However, they did not investigate the effect of eccentricity error in the experimental setup on the roundness error of hole profile.

D. Zhu and H. Y. Xu [5] investigated accuracy improvement of electrochemically drilled holes by using dual pole electrode tool. The idea was to localize electric field around machining zone to minimize over cuts. They used a finite element model to simulate the electric field distribution around the non-machining region. They showed, from simulation and experimental tests, a reduction in the conicity error of the machined holes.

2. Problem formulation

In the electrochemical sizing of holes, a disk like tool is passed through the hole at a certain feedrate, as shown in fig. 1. At the beginning of machining, the center of the tool must coincide with the center of the top section of the hole. This is necessary to avoid non-uniformity in the machining process due to variations in the gap between the tool and the hole walls. However, even with elaborate work concerning the centering of the tool and the hole, a minimum value of eccentricity can not be avoided. Therefore, such concentricity error must be taken into consideration when simulating inaccuracies in the process.

Also, for accurate finishing of holes, the direction of feed of the tool must, theoretically, coincide with the center line of the hole. Practically, a minimum value of alignment error is inherent to any industrial or laboratorial setup. The effect of misalignment on hole inaccuracy is amplified when machining holes with large aspect ratio; which is one on the main applications of electrochemical hole sizing processes. Therefore, the alignment error must be taken into consideration when simulating inaccuracies in electrochemically finished holes.

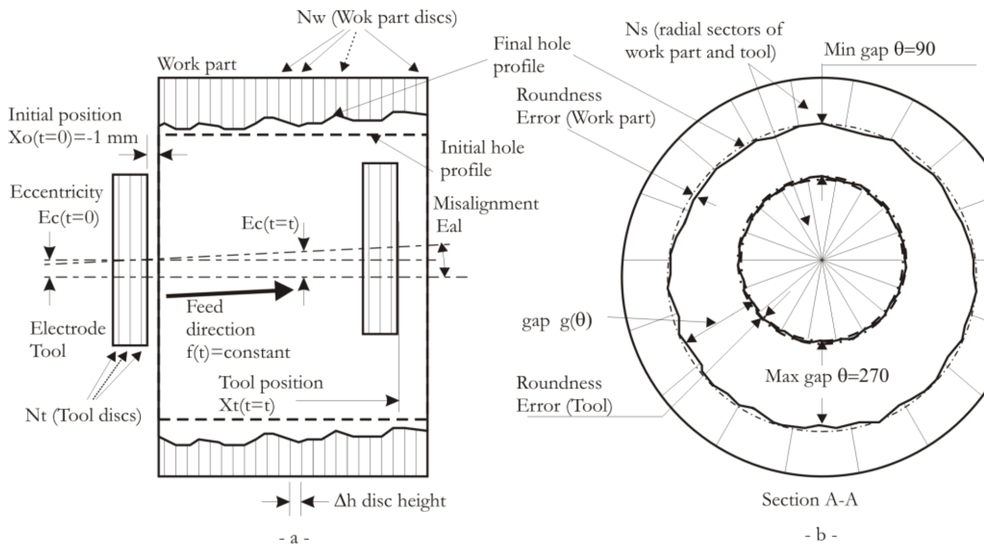

Fig. 1. Setup for the electrochemical sizing process.

Moreover, electrode tool roundness error is inherent to any tool due to its manufacturing process. Even if such roundness does not exist at a considerable level in the beginning of machining, it will develop due to non-faradaic dissolution or due to contamination or hard particles in the highly pressurized electrolyte. Therefore, tool roundness error must also be considered when simulating inaccuracies in electrochemically finished holes.

The above mentioned three parameters are the main factors affecting inaccuracy in the electrochemical finishing process and will be essentially considered in the simulations of the present work. However, more factors can affect process inaccuracy such as vibration of the tool due to the pressurized electrolyte and the variation in electrolyte temperature during machining. Feed drive dynamics can also affect accuracy of holes. But, such factors will not be considered in the present work.

3. Process simulation

The present work considers a work part with a through hole. The work part is simulated as a stack of Nw annual discs, simulation discs. Each disc has a height of Δh. The center line of the hole is perpendicular to the top surface of the work part (far left surface of the work part in the fig.1). This surface is considered a reference surface for the simulation. The tool is simulated as a stack of Nt discs each with the same height as the work part discs. The disc height controls the dimensional resolution of the simulation. In the present work a disk height of 10 μm is used.

The center line of the tool is eccentric with the center of the work part top disc hole by $Ec(t{=}0)$, fig. 1-a The initial position of the tool is shifted by Xo=-1 mm from the top work part disc. The tool is fed towards the work part at a constant feedrate $f(t)$. The direction of tool feed is inclined to the center line of the work part by an angle Eal. This represents alignment error in the actual setup for electrochemical sizing of holes.

At each time instant, the tool position is calculated as a function of the initial position of the tool and its feedrate and is given from the following equation, eq. (1). The Δt in the equation represents the time step of the simulation. The correlation between Δh, Δt and $f(t)$ is critical and is discussed in reference [6].

$$Xt(t=t) = Xo + \sum_{t=0}^{t=t} f(t).\Delta t \, . \tag{1}$$

The eccentricity between the tool and the hole varies according to the position of the tool and is given from the following equation, eq.(2):

$$Ec(t=t) = Ec(t=0) + Xt(t=t).Eal \, . \tag{2}$$

The tool and the work part are divided into Ns radial sectors. In the present simulations 40 radial sectors are considered, Ns=40. The gap between the tool and work part varies from one sector to another depending on the eccentricity and misalignment errors. The gap, $G(\theta)$ at any sector is approximately given by following equation assuming small values of concentricity error compared to tool radius.:

$$G(\theta) = Go(\theta=0) + Ec(t=t)\, sin(\theta) \, . \tag{3}$$

The sector angle θ is given by:

$$\theta(i) = (i-1) \times \frac{180}{Ns} \, . \tag{4}$$

The sector index i varies from 1 to Ns. The sector index i and the angle θ are redundant and are presented here for simulation purposes. The above two equations imply that the gap at any angle θ is larger than the gap at θ=90°. It also implies that the maximum gap is at angle θ=270°, as shown in fig. 2.

The tool roundness error is included as undulations on the surface of the tool. Because a slim disc like tool is considered in the present work, these undulations are fixed for all tool sections (simulation discs). The undulations are produced using a random number generator function. The height of these undulations represents the tool roundness error. The form and frequency of these undulations are randomly generated, fig. 1-b. However, the roundness error of the tool is determined as the radial distance between two concentric circles which envelope the tool profile. This error value is controlled by adjusting inputs to function of random number generator.

At each time step, the position of the tool is calculated and the amount of material removed during Δt is calculated. Then, the incremental change in the gap and consequently the incremental changes in hole profile at each simulation disc at each sector are determined. The simulation program is developed in the form of interconnected modules using the visual C/C++ programming language. Details of the structure of the computer program and programming methodology are not described in the present work.

4. Simulation results

A set of simulations were run to investigate the effects of the afro mentioned parameters on the hole profile roundness error and hole walls straightness error. Global simulation parameters are listed in table 1. These parameters are fixed for all simulation runs.

Fig. 3-a shows, comparatively, the distortion in the hole profile due to concentricity error. The solid line profile represents the case of zero concentricity error. It looks like a true circle. However, the dashed line profile was obtained when simulating a 50 μm eccentricity. The difference between the two profiles is due to non uniform machining due to variations in the gap between the tool and the hole. These two profiles are constants over the length of the hole. The variation in the hole radius is shown in fig. 2-b. These variations are typical for setups with eccentricity errors.

Fig. 2-c shows the effect of concentricity error on the mean roundness error of the hole. Hole roundness error is determined by calculating the least square circle of its profile. Then, two concentric circles are selected to envelop the profile with minimum radial distance between them. This minimum distance is the roundness error of the profile. The mean roundness error implies the mean values of the roundness errors of simulation discs along the length of the hole. From the figure, it is clear that eccentricity error results in a proportional increase in the mean roundness error of the hole. Also, the same figure shows that there is no variations in the roundness error of simulation discs along the hole length. This zero variations is expected as all sources of setup errors are ignored in this simulation, except concentricity error.

The effects of alignment error on straightness error of hole walls are shown in fig. 3. Fig. 3-a shows the hole profile of the simulation disc at the reference surface of the work part, solid line. It, also, shows hole profiles at simulation discs 50 mm away from the reference surface. The variations in hole radii for these simulation discs are shown in fig. 3-c. The misalignment value in this simulation was 400 μm /m. It is clear that there is an increased distortion in profile of the hole away from the reference surface. The distortion resembles the effect of increased concentricity error. This is expected as misalignment is equivalent to an increase in eccentricity along the length of the hole.

Fig. 3-b shows the variations in the radius of the hole along hole length at sector indices 0, 10 and 20 (0, 90 a 180 degrees respectively). It is clear that at sector index 0 there is subtle variations in the radius of the hole. This is because the tool travels away form this sector along the hole length resulting in increased gap and consequently sluggish machining rate. Maximum variation in hole radius takes place at sector 10 at angle 90 degrees.

Fig. 3-d shows the variations in the straightness error of hole walls for alignment errors of 400 and 100 μm /m. Straightness error is determined as the distance between

Table 1
Global simulation parameters

Atomic weight	55.85 [amu]	Tool diameter	4.5 mm
Density	7870 [kg/m^3]	Tool height	1.1 mm
Conductivity	25 [1/Ω/m]	Work part diameter	4.6 mm
Valency	2	Work part height	50 mm
Feedrate	3.6 mm/min	Potential	35 volts

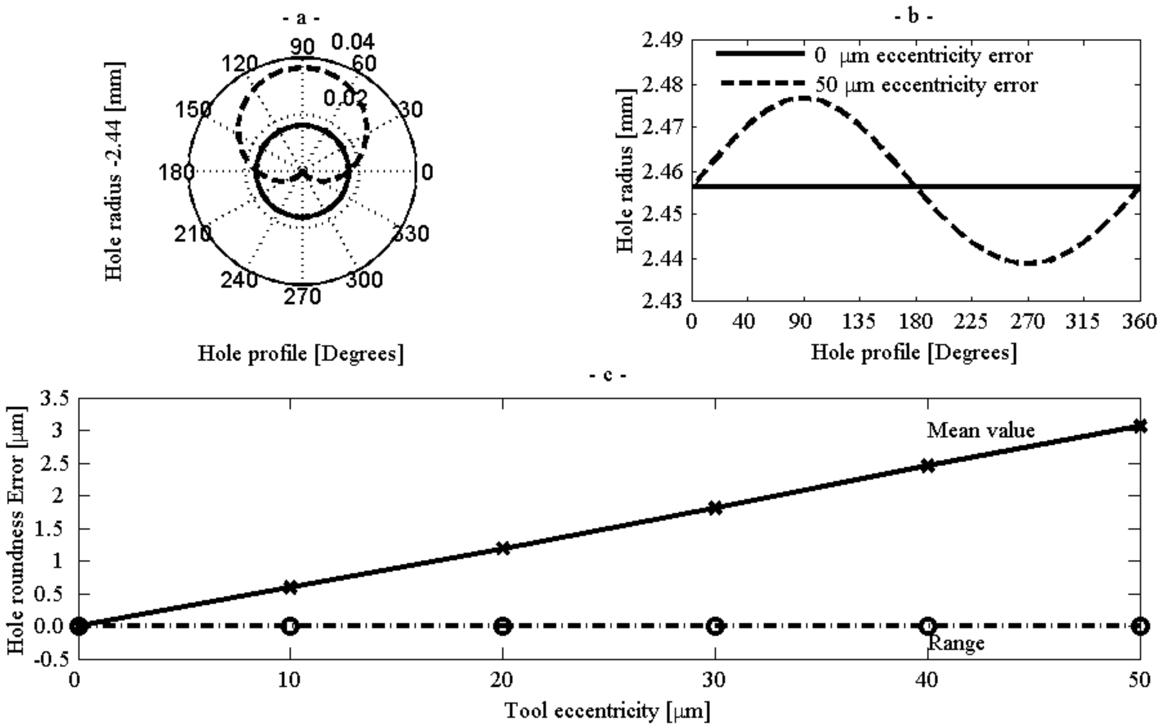

Fig. 2. Effect of eccentricity error on hole profile and roundness of the hole.

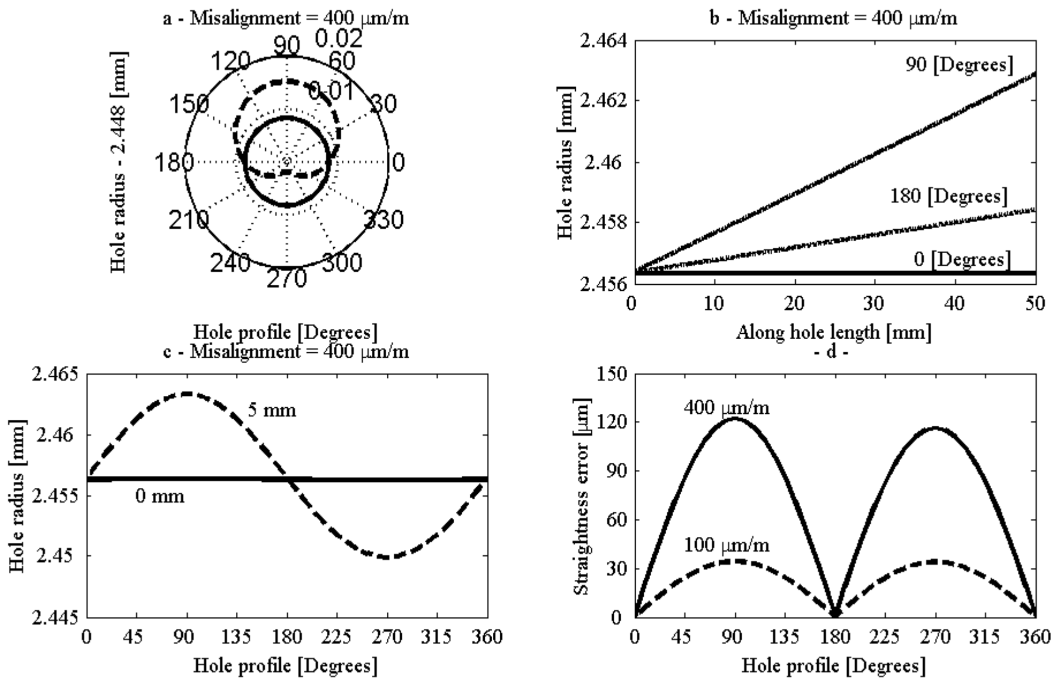

Fig. 3. Effect of misalignment error on hole profile and straightness error.

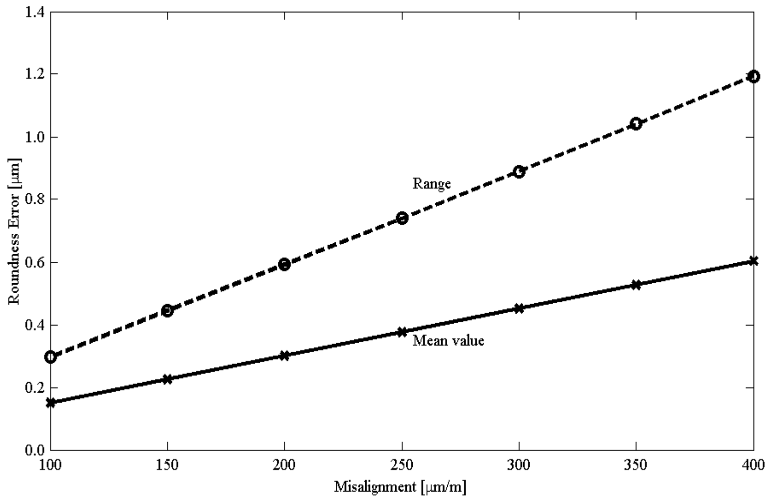

Fig. 4. Effect of misalignment error on mean value and range of hole roundness error.

two straight lines which envelop the hole side at specified sector taking into account the general direction of the hole side. From the figure it is clear that maximum straightness error takes place at sectors 10 and 30 at angles 90 and 270 degrees respectively. The figure also shows that larger alignment error results in larger maximum straightness error. The effect of misalignment error on the hole roundness error is shown in fig. 4. From the figure, it is clear that an increase in misalignment error results in a proportional increase in the mean hole roundness error. It, also, results in an increase in the range of hole roundness error along hole length.

The effect of tool roundness error on hole profile is shown in fig. 5. Fig. 5-a shows hole profiles produced using two tools with different roundness errors. The first hole profile, dashed line, is produced using a tool having 6 μm roundness errors. The second hole profile, solid line, is produced using a tool with 25 μm roundness errors. Fig. 5-c shows the variations in hole profile radius. From the figures, it is clear that increasing the tool roundness error results in an increase in the roundness error of the hole. Figs. 5-b and 5-c show that the roundness errors are constants along the hole length. In this simulation all setup errors except tool roundness errors are zeroes. The eccentricity error of the hole profile shown in the figure is obtained as the deviation of the center of the calculated least square circles of the profile and the center of the tool. This error depends on the random form of the tool as printed on the hole profile and it is constant along hole length. The value of this error is very small compared to the value of roundness error. as shown in figure.

Fig 6-a shows that the hole profile roundness error is proportional to the tool roundness error. It also shows that roundness error of the hole is smaller than that of the tool. This means that hole roundness error is weakly insensitive to tool roundness error, or, in other words the electrochemical sizing process tends to reduce the effect of the tool roundness error on hole roundness error which is an inherent advantage of the process [7]. Fig. 6-b shows the standard deviation in the roundness and eccentricity errors of the hole. From the figure, it is clear that the variations in these errors are extremely small.

5. Conclusions

Simulation based analysis of effects of errors in setup of hole electrochemical sizing process on inaccuracies in holes produced by the process showed a strong correlation between setup errors and hole inaccuracy. Eccentricity resulted in a distortion of the hole profile and, consequently, hole roundness error. Misalignment resulted in non-uniform distortion of the hole profile over hole length. It also resulted in a non-uniform straightness error of hole walls. Mean hole roundness error was found to be directly proportional to both alignment and concentricity errors. Tool roundness error is printed on hole profile at a smaller scale, thus, resulting in roundness and eccentricity errors of the hole profile. Hole eccentricity error is much smaller than roundness error of the tool.

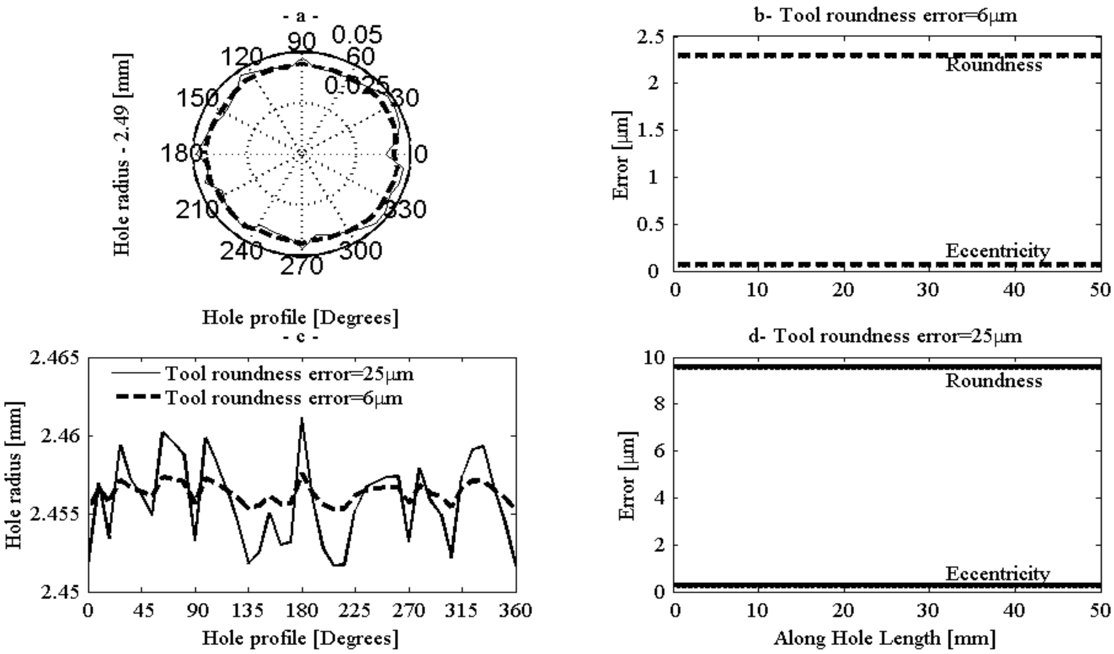

Fig. 5. Effect of tool roundness error on hole profile.

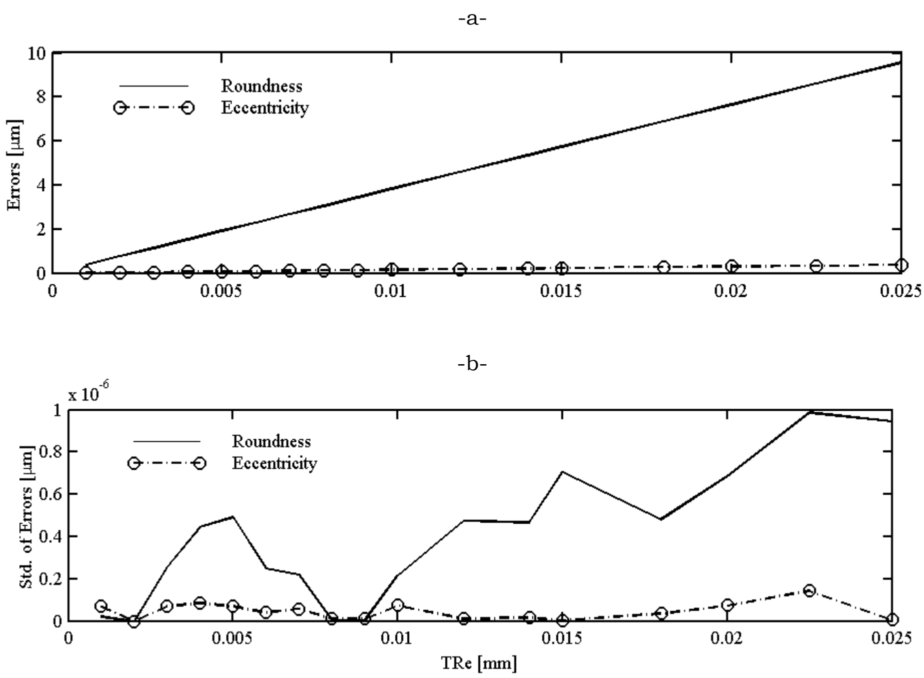

Fig. 6. Effect of tool roundness error on hole profile and hole eccentricity.

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Received December 8, 2005
Accepted February 20, 2006