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A Comparative Performance Analysis of Uncoated and Coated WC Drills during Forging Brass Drilling Operation

Manit Timata, Anurat Wisitsoraat, and Charnnarong Saikaew

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In this study, the performances of the WC tools coated with TiCN and AlCrN by filter cathodic arc in hole drilling of forging brass were investigated and compared with that of uncoated one. The performances were evaluated using the exit burr height (EBH) criterion and process capability indices as a function of number of parts drilled with the three types of drills. The results showed that there were significant differences of EBH and the process capability index of *Cpm* during drilling of the workpieces with the three types of drills. The desired EBH values of 0.152-0.1535 mm, roughness values of 2-3 µm and drilled diameters of 17.79-17.8 mm were achieved with the appropriate operating conditions including cutting speeds and feed rates ranging from 0.17 to 0.19 mm/rev and 55 to 57 m/min, respectively.

Keywords brass, burr height, coating, drilling, process capability analysis

1. Introduction

TiCN is used to protect surface wear, corrosion and friction due to its excellent properties such as high hardness, high elastic modulus, low friction coefficient (Ref 1, 2) and heat transfer coefficient (Ref 3). The tribological performances of TiCN coatings have been experimentally investigated under dry and wet conditions at various temperatures. Hernández-Sierra et al. (Ref 4) compared the wear performances of TiN- and TiCN-coated AISI H13 tool steel under wet and dry conditions using a pin-on-disk wear test. TiCN was found to be more appropriate than TiN for coating on AISI H13 steel owing to low friction coefficient and wear rate characteristics. Zhong et al. (Ref 5) assessed the performances of the TiN-, TiAlN- and TiCN-coated WC inserts in milling quenched and tempered 40Cr steel under dry, long cutting lengths and high cutting speed conditions. The results showed that TiAlN- and TiCN-coated inserts exhibited much lower flank wear than TiN.

Like TiCN, AlCrN is usually used for wear protection in many high-performance metal-cutting applications. AlCrN-coated cutting tools have better wear resistance than TiAlN-coated tools due to its lower thermal conductivity than that of TiAlN resulting in less heat dissipation into the cutting tools (Ref 6). There have been many studies employing AlCrN-coated WC tools in machining operations of a variety of materials. For instance, Lakshmanan (Ref 7) evaluated the performances of AlCrN-coated WC insert and uncoated one in turning of Ti-6Al-4V alloy under wet and dry conditions and investigated the effect of cutting speed, feed rate and depth of cut on average surface roughness (Ra), cutting force and wear resistance. They reported that the coated insert exhibited better cutting performance and better wear performances than the uncoated one under cryogenic coolant condition, which was attributed to the reduction in the cutting zone temperature and friction. In milling AISI 1045 carbon steel, Kalss et al. (Ref 8) studied the machining performance of AlCrN-, TiAlN-, AlTiN- and TiCN-coated solid carbide end mills. The tool life of the AlCrN-coated end mill was found to be much longer than those of the others at higher cutting speed owing to the better oxidation resistance and thermal stability.

Drilling is an important machining operation, which accounts for about 33% of all machining operations. TiCN-coated tools have been extensively used for drilling of a variety of materials. For example, Chen et al. (Ref 9) studied the drilling performances of TiN-, TiAlN- and TiCN-coated drills against austenitic stainless steel workpieces under dry condition. The study revealed that TiCN had the longest tool life because carbon element infiltrated into the rake face of the drill and formed carbides, leading to improved hardness and wear resistance. Likewise, Zhong et al. (Ref 5) found that TiCN-coated drills exhibited lower flank wear after drilling 2000 holes than TiAlN and TiN owing to their superior hardness, toughness and oxidation resistance compared with those of TiAlN and TiN coatings.

Meanwhile, AlCrN-coated tools have also been used in drilling of various materials. For instance, de Paiva Jr. et al. (Ref 10) investigated the tool characteristics of TiAlN/TiN, AlCrN and TiSiN/AlCrN-coated WC drills on compacted graphite iron. They found that the tool lives of the Cr-based coating tools were much longer than that of TiAlN/TiN at a drilling speed of 80 m/min because Cr and Al in AlCrN as well as Si, Al and Cr in TiSiN/AlCrN improved thermal stability. Moreover, Tekaüt et al. (Ref 11) reported that there were statistically significant differences of the total deformation occurred in the outermost region of the drill cutting edge and stress components occurring on the AlCrN-coated and uncoated

Manit Timata and **Charnnarong Saikaew**, Department of Industrial Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand; and **Anurat Wisitsoraat**, National Electronics and Computer Technology Center, Pathumthani 12120, Thailand. Contact e-mail: charn_sa@kku.ac.th.

solid helical carbide drills while drilling AISI H13 hot work steel.

A burr is a critical problem of drilling operation that directly affects the operating costs depending upon the complexity of drilled parts and the precision of hole shape and size (Ref 12). It is the portion of a drilled workpiece formed on an edge or a surface that lies outside the desired geometry (Ref 13). Burr significantly influences product dimensional errors and productivity (Ref 14). Deburring procedure is one of the possible ways to solve such the burr formation problems but the deburring procedure is not preferred due to its very high operating cost (Ref 13). Gillespie stated that the burr reduction process can account for 30% of the total operating cost (Ref 15).

Exit burr height (EBH) is used as a criterion for evaluating the burr problem and quality of a drilling process (Ref 3, 16, 17). A drilling process is typically optimized in terms of the EBH and target hole diameter in order to meet the customer's requirements, minimize production cost and increase productivity. Altan and Altan (Ref 3) investigated the effect of drilling speeds (30, 40, 50 m/min) and feed rates (0.006, 0.0125, 0.250 mm/rev) on the average EBH and surface roughness of ultra-high molecular weight polyethylene workpieces using TiN-coated, TiCN-coated and uncoated HSS twist drills. The feed rate was indicated to be the statistically significant factor of the average EBH, which evidently decreased with increasing feed rate. Similarly, Shanmughasundaram and Subramanian (Ref 17) studied the influence of feed rate, spindle speed, step angle and step size on the average EBH of drilled Al-graphite composites using 6-mm-diameter carbide step drills using the L27 orthogonal array of Taguchi's parameter design and analysis of variance (ANOVA) to determine the optimal operating condition for a minimum EBH. The feed rate, step angle and step size were stated to be the most significant factors affecting the average EBH with the optimal feed rate, spindle speed, step angle and step size of 0.06 mm/rev, 600 rpm, 40° and 1 mm, respectively. Likewise, Bahce and Özdemir (Ref 14) considered the effect of spindle speed, feed rate and exit surface angle on the average EBH of Al7075 workpieces with various free-form surfaces by employing HSS drilling tools according to the DIN 338/RN standard using the Taguchi's parameter design and ANOVA for the optimization of EBH. Furthermore, the performances of special uncoated (Ref 18) and AlCrN-coated drills (Ref 19) were investigated based on the EBH and drilled diameter data set from drilling of forging brass. The cutting speed and the feed rate also had statistically significant effects on both data at the significance level of 0.05 and the appropriate drilling condition comprising cutting speed and feed rate of the uncoated and AlCrN-coated WC drills was obtained using ANOVA, response surface methodology (RSM) (Ref 18) and Monte Carlo simulation methods (Ref 19).

According to the literature survey, there are some drilling studies of brass or hardened brass using AlCrN-coated tools but no such study using TiCN-coated drills. Since the drilling performances depend considerably on the tool and workpiece materials, it is compelling to fill the research gap of brass drilling with TiCN-coated tools. In this work, the performances of the WC tools coated with TiCN by filter cathodic arc in hole drilling of forging brass were investigated and compared with those of uncoated and AlCrN-coated ones. In addition, the drilling process was systematically conducted and optimized based on the EBH criterion using central composite design (CCD), analysis of variance (ANOVA) and response surface methodology (RSM) coupled with overlaid contour plot investigation and sensitivity analysis. Moreover, the process capability indices including Cp, Cpk and Cpm combined with the percentage of the specifications' width were used to analyze the comparative performances of the drilling tools with different numbers of drilled parts.

The process capability indices have been used to evaluate and compare the performances of manufacturing processes under identical analytical conditions useful for process improvement and quality control. In particular, Cp and Cpk indices are commonly applied to assess the suitable process potential capability, precision and performances of manufacturing processes. For instance, Dolinsek and Kopac (Ref 20) monitored process variation with statistical process control charts to detect the specific causes of process variations and used Cp index for measuring the process capability during turning the crank shaft made from lamellar cast iron DIN 1691:05.85 and demonstrated the ability to determine the accuracy of machined parts and consistencies of machine/cutting tools. In addition, Motorcu and Güllü (Ref 21) applied statistical process control charts to control machining stability by detecting specific causes from the cast iron manufacturing process conditions, cutting tool life expiration and machine parameter settings for turning and drilling spheroidal cast iron and employed Cp and Cpk to determine if the diameters of machined parts were within the specification limits. Moreover, the Cpm index would be used to take into account of process centering related to a process target if Cp and Cpk indices failed to do (Ref 22). Pearn et al. (Ref 23) employed Cp, Cpk, Cpm indices to identify whether the audio-speaker driver manufacturing process was able to meet the frequency specification of 80 ± 10 Hz for 3-in. audio-speaker drivers and could indicate the significant process factors causing the product quality problem, leading to proper adjustment of machine settings. Hence, the approach based on the three process capability indices would provide an easily understandable indicator to compare the brass-drilling performances of the three types of drills based on the EBH criterion.

2. Experimental and Methods

2.1 Materials and Experimental Procedure

Yellow brass (model JIS-C3771) was used to produce a water-valve component by the forging manufacturing process under real working conditions. The chemical compositions in wt.% of the brass were 37.82% Zn, 56.15% Cu, 3.22% Pb, 0.154% Fe, 0.081% Sn, 0.042% Ni, 0.025% Sb, 0.014% As, 0.002% Mn and 0.0017% Mg.

Figure 1 illustrates the experimental procedure for drilling forging brass. The special drill was fabricated for drilling the two specific holes of the water-valve component. The drill was designed to minimize burr formation due to its special drill's geometry. The CNC drilling machine (Number Five: model DR-8P) was employed throughout all experiments in this study. The drill was made of tungsten carbide (WC) and prepared by sintering process (class K20, DIN: DK 255F) (Ref 18, 19). All

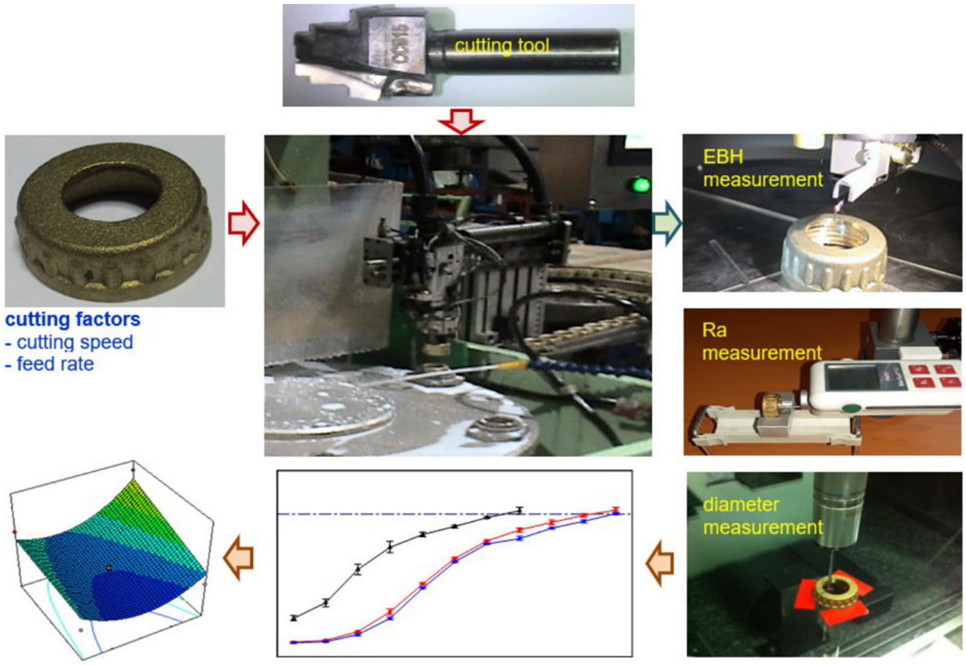

Fig. 1 Experimental procedure for the drilling study

drills were coated with TiCN and AlCrN by a filtered cathodic arc (FCA) system equipped with two material targets and the proprietary straight duct filters. All drills were precleaned using detergent and sonicated with alcohol for 30 min and then placed into the FCA chamber followed by evacuation to a base pressure of 5×10^{-3} Pa. The thickness of TiCN and AlCrN coatings was approximately 3 μm measured by a commercial stylus profiler (Bruker model Dektak®). The mechanical and tribological properties of TiCN coating were reported by the manufacturer with a hardness of 90 HRA, an elastic modulus of 415 GPa and a friction coefficient of 0.05, whereas those of AlCrN coating had a hardness of 92 HRA, an elastic modulus of 620 GPa and a friction coefficient of 0.28 (Ref 24).

Throughout the drilling performance tests, 2000 workpieces were drilled with the constant cutting speed of 50 m/min and the feed rate of 0.2 mm/rev using one of four uncoated, TiCN- and AlCrN-coated WC drills. The EBH values of randomly selected 130 drilled parts were measured at three positions using a burr height measuring instrument (Bruker: model Dektak XT) and the average EBH was determined from the three observations of each part. The workpieces were continuously machined, and the EBH measurements were recorded after drilling the other 2000th parts until reaching the EBH criterion of 0.16 mm. Twenty-six subgroups of five drilled parts each were assigned to investigate the variability of the EBH measurements using control charts and enable further process capability analysis.

Surface roughness testing machine (Germany, Mahr model: MarSurf PS1) was used to measure average roughness (Ra) values of drilled workpieces at four random positions on each workpiece with a cut-off length of 0.8 mm and a sampling length of 5 mm. Drilled hole diameter was measured using a coordinate measuring machine (CMM) (United States of America, Werth model: ScopeCheck FB) at three axial positions from hole entry. The appropriate operating conditions of drilling factors were determined using RSM and overlaid plots with sensitivity analysis.

2.2 Process Capability Analysis

Quality is defined by customers who set whether a product has met or exceeded their requirements and satisfactions. Manufacturer needs to translate the customers' requirements into measurable quality characteristics. The specification limits for the quality characteristics set by the manufacturer typically include the upper specification limit (*USL*) and the lower specification limit (*LSL*). *USL* is the highest value that a quality characteristic can have according to customers' requirements while *LSL* is the lowest value that is considered to be conforming. Process capability is the ability of a process to consistently meet the customers' requirements (Ref 25). A process capability index is an aggregate measure of a process ability to meet the specification limits (Ref 26).

Generally, *Cp* is referred to the index used to measure process capability of producing a product that meets specification limits and customers' requirements. The index of *Cp* was introduced by Juran (Ref 27). Practically, the *Cp* is used to determine the system's location in specification limits and defined as a ratio of the specification spread to the process spread. Hence, the *Cp* index is expressed as:

$$Cp = \frac{USL - LSL}{6\hat{\sigma}_{ST}} \quad \text{(Eq 1)}$$

The difference between *USL* and *LSL* represents the specification spread, whereas the 6-sigma defines the process spread that is 6 times of the within-subgroup standard deviation. If a process average is equal to the halfway point between the *LSL* and *USL*, the *Cp* value is 1 indicating that approximately 99.73% of the data set will be within the specification limits. If the *Cp* value is less than 1, the process is not highly capable of meeting the customers' requirements (Ref 25). Normally, many manufacturers require the *Cp* index as high as 1.33, 1.5 or 2. However, the *Cp* index does not indicate the location of the data. Kane (Ref 28) proposed the *Cpk* index to evaluate the distance from the process mean to the closest specification limit that is 3 times of the within-subgroup standard deviation. Thus, the *Cpk* index is written as:

$$Cpk = \min\left(\frac{USL - \bar{y}}{3\hat{\sigma}_{ST}}; \frac{\bar{y} - LSL}{3\hat{\sigma}_{ST}}\right) \quad \text{or} \quad Cpk = \min(CPU; CPL) \qquad \text{(Eq 2)}$$

It is noted that the indices of *Cp* and *Cpk* will be equal when the system is centralized at the target value and *Cpk* cannot be greater than the *Cp*. If the specifications of a product deviate from the target values, it means that the quality of the product does not meet the customer's requirements and satisfaction (Ref 25). The larger values of both indices dictate the better the performance of the process. It is also noted that the inverse of the capability of the process (1/*Cp*)100% represents the percentage of the specifications' width used by the process.

The *Cpk* index only expresses the spread between the process mean and the closest specified limit. However, it does not include the spread of the process control and does not take into account the variations when the process mean fails to meet the specified target but is still within the customer's specification limits. *Cpm* is one of process capability indices used to measure if the process meets specification and is on a target value. The *Cpm* index compares the specification spread with the spread of data and takes into account the data's deviation from the target value instead of its deviation from the process mean. If the distance between the target and the observations is large, the value of *Cpm* index is small. The value of *Cpm* index increases as the process improves and approaches the target (Ref 25). The *Cpm* index is defined as:

$$Cpm = \frac{USL - LSL}{6\,\psi_{ST}} \qquad \text{(Eq 3)}$$

where

$$\psi_{ST} = \sqrt{\sigma_{ST}^2 + (\bar{y} - m)^2} \qquad \text{(Eq 4)}$$

and $\bar{y}$ represents the average of a quality characteristic of the process, whereas m is a target value which was specified as the EBH criterion of 0.16 mm.

In this work, EBH is the quality characteristic having only a *USL* (0.16 mm). Hence the *CPU* was used to measure the machining performance of the uncoated, TiCN and the AlCrN-coated WC drills. The larger *CPU* value indicates the better the capability of the machining performance.

3. Results and Discussion

3.1 Preliminary Analysis

Figure 2 illustrates the normal probability plots of the average EBH after drilling the 2000th, 10,000th and 22,000th parts using the uncoated and TiCN and an AlCrN-coated WC drills. The normal probability plot demonstrates that the plotted points of the average EBH of each data set roughly form a straight line. The Anderson–Darling (AD) normality tests give all p values less than the significance level of 0.05 for the average EBH after drilling the 2000th, 10,000th and 22,000th parts using the uncoated, TiCN and an AlCrN-coated WC drills. This confirms that the normal probability distributions fit the data sets of the EBH values quite well and the data sets can be used to perform other statistical analyses.

It is also clear that the averages EBH during drilling of the workpieces using the uncoated drill are significantly larger than those of the TiCN- and AlCrN-coated WC drills. The difference is ranging from 0.03 to 0.1 mm. However, the averages EBH for TiCN- and AlCrN-coated WC drills are not significantly different. Nevertheless, Kalss et al. (Ref 8) found that the averages flank wear in milling AISI 1045 carbon steel using TiCN-coated end mills were dramatically higher than those of the AlCrN-coated ones, which could be attributed to the higher abrasive wear resistance of the AlCrN coating.

In addition, the trend lines of the averages EBH display two dispersive regions, which exhibit different slopes for all drills after drilling of 2000 holes. On the other hand, the averages EBH have very similar trend lines after drilling of 10,000 holes but the averages EBH values are not significantly different after drilling of 10,000 holes and 22,000 holes using the two coatings. Hence, the other statistical and quality tools are needed to further analyze the performances of the two coatings.

Figure 3 depicts the variation of EBH versus the number of drilled parts. The EBH values after drilling workpieces with four uncoated drills exhibit a larger variation than those with four TiCN- and AlCrN-coated WC drills. The numbers of drilled parts before reaching the EBH criterion are 16,000 and 22,000 for drilling with the uncoated and TiCN- or AlCrN-coated WC drills, respectively. Hence, the results confirm the significantly different machining performances of the uncoated drills and the two types of coated drills. This can be attributed to the high hardness and good wear resistance of TiCN and the AlCrN coatings at low temperatures compared with those of WC and other coatings (Ref 29, 30). In addition, the uncoated WC drill exhibits higher heat transfer coefficient, friction coefficient and thermal conductivity than the TiCN- and AlCrN-coated WC drills (Ref 1, 3, 31). As the temperature in the cutting zone during drilling with the uncoated drill increases, the deformation of the forging brass workpiece material increases, resulting in heat dissipation along the drilled hole as well as the heat expansion in cutting zone leading to a higher EBH. In addition, an increase in EBH is observed as the number of drilled parts increases because many drilled parts generate more heat due to friction and increase the time for heat dissipation through the uncoated drill. On the other hand, less heat generated in cutting zone will be distributed along the feed direction of the drilled hole when drilling with the TiCN- and AlCrN-coated WC drills, resulting in a lower EBH.

Practically, control charts are used to control process measurements with the assumption that the measurements follow the normal distribution (Ref 25) as illustrated in Fig. 2. When a process measurement can be controlled by controlling its average and variability. Since the average and variability are statistically independent, $\bar{X}$ chart from a sample average will be used to control the process mean while R chart employing a sample measure of variability will be separately applied to control the process standard deviation. Figure 4 illustrates $\bar{X}$ and R charts for EBH after drilling the 2000th, 10,000th and 16,000th parts using one of the uncoated drills, whereas Fig. 5 shows the two charts for EBH after drilling the 2000th, 10,000th and 22,000th parts using one of the TiCN-coated WC drills. In the control charts, EBH values from 26 subgroups (samples) of five drilled parts were collected after drilling the

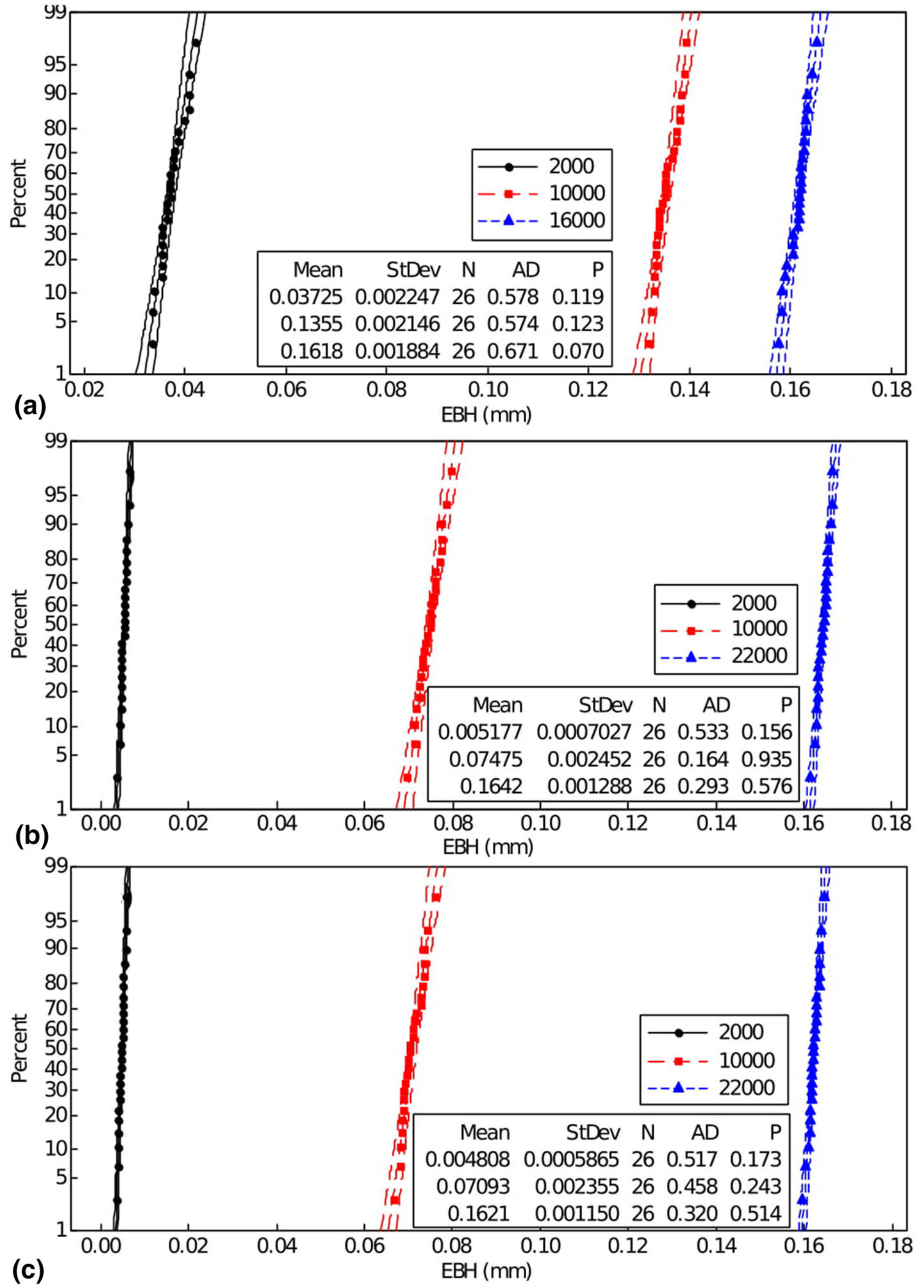

Fig. 2 Normal probability plots of the average EBH using the (a) uncoated drill after drilling the 2000th, 10,000th and 16,000th parts using (b) TiCN and (c) AlCrN-coated WC drill after drilling the 2000th, 10,000th and 22,000th parts

2000th to 16,000th drilled parts using one of the four uncoated drills as well as the 2000th to 22,000th drilled parts using one of the four TiCN-coated WC drills. According to Fig. 4 and 5, all sample means and ranges were in control indicating that there were no obvious unassignable causes. Likewise, EBH values were also used to control process measurements after drilling the 2000th to 22,000th drilled parts using one of the AlCrN-coated WC drills (figure not shown). The variability was small enough to entirely meet the customer's specifications with the EBH criterion of 0.16 mm. Next, the process capability would be assessed using the capability indices of *Cp*, *Cpk* and *Cpm* for comparative analysis of the uncoated, TiCN- and AlCrN-coated WC drills in forging brass drilling operation.

3.2 Process Capability Analysis

Figure 6 and 7 show the process capability outputs based on EBH data from Minitab® software after drilling the 2000th, 10,000th and 16,000th parts using an uncoated drill and after drilling the 2000th, 10,000th and 22,000th parts using a TiCN-coated WC drill, respectively. The process capability outputs after drilling the 2000th to 22,000th parts using one of the AlCrN-coated WC drills were also obtained but omitted for presentation conciseness. The histograms along with the normal distribution curves present the process outputs relative to the specification limits based on the customer's requirements (the average EBH of 0.16 mm). In order to determine the *Cp*, *Cpk* and *Cpm* values, the *USL* as the target for the maximum EBH

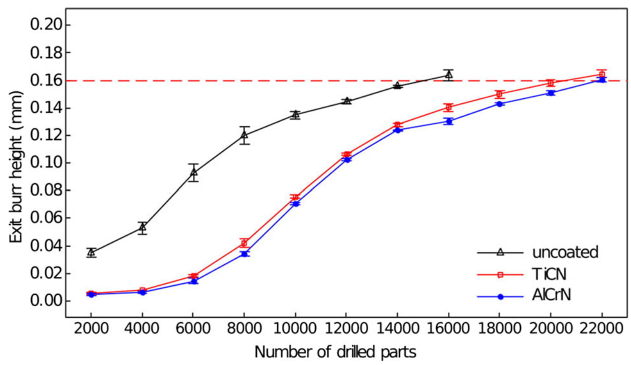

Fig. 3 EBH vs. the number of drilled parts using the uncoated, TiCN- and AlCrN-coated WC drills

value of 0.16 mm and the *LSL* value of 0 mm were specified in the software input. The basic capability indices of the drilling process with the uncoated, TiCN- and AlCrN-coated WC drills were computed using Eq 1 and 2. To demonstrate how to obtain the *Cp* and *Cpk* values, let $\hat{\sigma}_{ST}$ be the standard deviation of EBH, which was equal to 0.00576 mm and $\bar{y}$ be an average EBH, which was equal to 0.0372 nm after drilling the 2000th parts with an uncoated drill. For example, the *Cp* and *Cpk* values were determined as follows:

$$Cp = \frac{USL - LSL}{6\hat{\sigma}_{ST}} = \frac{0.16 - 0}{6 \times 0.00576} = 4.63 \quad \text{(Eq 5)}$$

and

$$Cpk = \min\left(\frac{USL - \bar{y}}{3\hat{\sigma}_{ST}}; \frac{\bar{y} - LSL}{3\hat{\sigma}_{ST}}\right) = \min\left(\frac{0.16 - 0.0372}{3 \times 0.00576}; \frac{0.0372 - 0}{3 \times 0.00576}\right) = \min(7.11, 2.16) = 2.16 \quad \text{(Eq 6)}$$

The *Cpm* index for the drilling process with the uncoated, TiCN- and AlCrN-coated WC drills were determined using Eq 3. The *Cpm* value could be calculated as follows:

$$Cpm = \frac{USL - LSL}{6\psi_{ST}} \quad \text{(Eq 7)}$$

where

$$\psi_{ST} = \sqrt{\sigma_{ST}^2 + (\bar{y} - m)^2} = \sqrt{0.0576 + (0.0372 - 0.16)^2} = 0.1227 \quad \text{(Eq 8)}$$

Thus,

$$Cpm = \frac{USL - LSL}{6\psi_{ST}} = \frac{0.16 - 0}{6 \times 0.1227} = 0.22 \quad \text{(Eq 9)}$$

Part per million (*PPM*) defectives is another process quality parameter that is calculated by measuring how many drilled parts are outside the criterion of EBH of 0.16 mm for every one million drilled parts produced. Figure 6(a) shows that the *Cpm* value is 1.41 after drilling the 2000th part while the *PPM* defectives is zero. After drilling the 10,000th part (Fig. 6b), the *Cpm* value decreases to 0.39 and the *PPM* value increases to 0.78 when the average EBH fails to meet the specified target (EBH = 0 mm) but is still within the specification limits. This indicates that there is still a source of defects although any variation from the target spreads within the specification limits. In addition, Fig. 6(c) also illustrates that the average EBH (0.1618 mm) is outside the specification limits and fails to meet the specified target when the *PPM* defectives substantially increases after drilling the 16,000th parts. Figure 7(c) also shows the similar results to Fig. 6(c), but more parts (22,000) can be produced using one of the TiCN-coated WC drills.

All *Cp* values obtained from EBH measurements after drilling with different drills at different numbers of drilled parts until reaching the EBH criterion of 0.16 mm are presented in Fig. 8. The *Cp* values are not significantly different between using the uncoated and the two types of coated drills at all of the different numbers of drilled parts. However, it is clear that when using the uncoated drills, the variability of *Cp* values was higher than that during using the TiCN- and AlCrN-coated WC drills. It should be noted that the values of *Cp* were not determined after drilling the 16,001th workpieces for the uncoated drill and 22,001th drilled part using the TiCN- and AlCrN-coated WC drills because EBH values were larger than the customers' requirement (0.16 mm).

Figure 9 shows the percentage of the specifications' width used by the process versus the number of drilled parts using the uncoated, TiCN- and AlCrN-coated WC drills. It is observed that the values of (1/*Cp*)100% for both coated drills are higher than those for the uncoated ones after drilling the 8000th drilled part. This implies that drilling operations with the two types of coatings account for higher percentage of the specifications' width after drilling the 8000th part than before drilling the 8000th drilled part. However, the variations of (1/*Cp*)100% values obtained from the coated drills are not statistically significant. Like *Cp*, the values of (1/*Cp*)100% were not determined after drilling the 16,001th part with the uncoated drill and the 22,000th part using the TiCN- and AlCrN-coated WC drills because the EBH values were larger than the customers' specification limits.

Figure 10 illustrates the *Cpk* values versus the number of drilled parts using the three types of drills. It is clear that the average values and variations of *Cpk* for the uncoated drills are very high and higher than those for the two types of coatings before drilling the 8000th drilled part. However, the variations of *Cpk* for all drills were not statistically significant after drilling the 8001th and 12,000th drilled parts. Upon drilling the 12,001th and the 14,000th drilled parts, the average values of *Cpk* for coated drills are much higher than those for the uncoated ones. After drilling the 14,001th workpiece, the variations of *Cpk* for the coated drills are not significant whereas the values of *Cpk* for uncoated drills cannot be obtained. Obviously, the values of *Cpk* could not be determined after drilling the 20,001th drilled part because the EBH was larger than the customers' requirement.

As mentioned earlier, *Cpm* is one of the most useful process capability indices employed to take into account of process target (Ref 22, 23). This research studied the comparative analysis of drilling tools made with different type of materials when the value of EBH was given as the performance criterion. Thus, the *Cpm* index is appropriate for the process criterion with the EBH of less than 0.16 mm. Figure 11 depicts the variations of *Cpm* for EBH after drilling the workpieces using all drills. Obviously, the values of *Cpm* using the coated drills are considerably higher than that using the uncoated drills. Thus, the coated drills improve the process and productivity of the forging brass drilling. However, the differences of *Cpm*

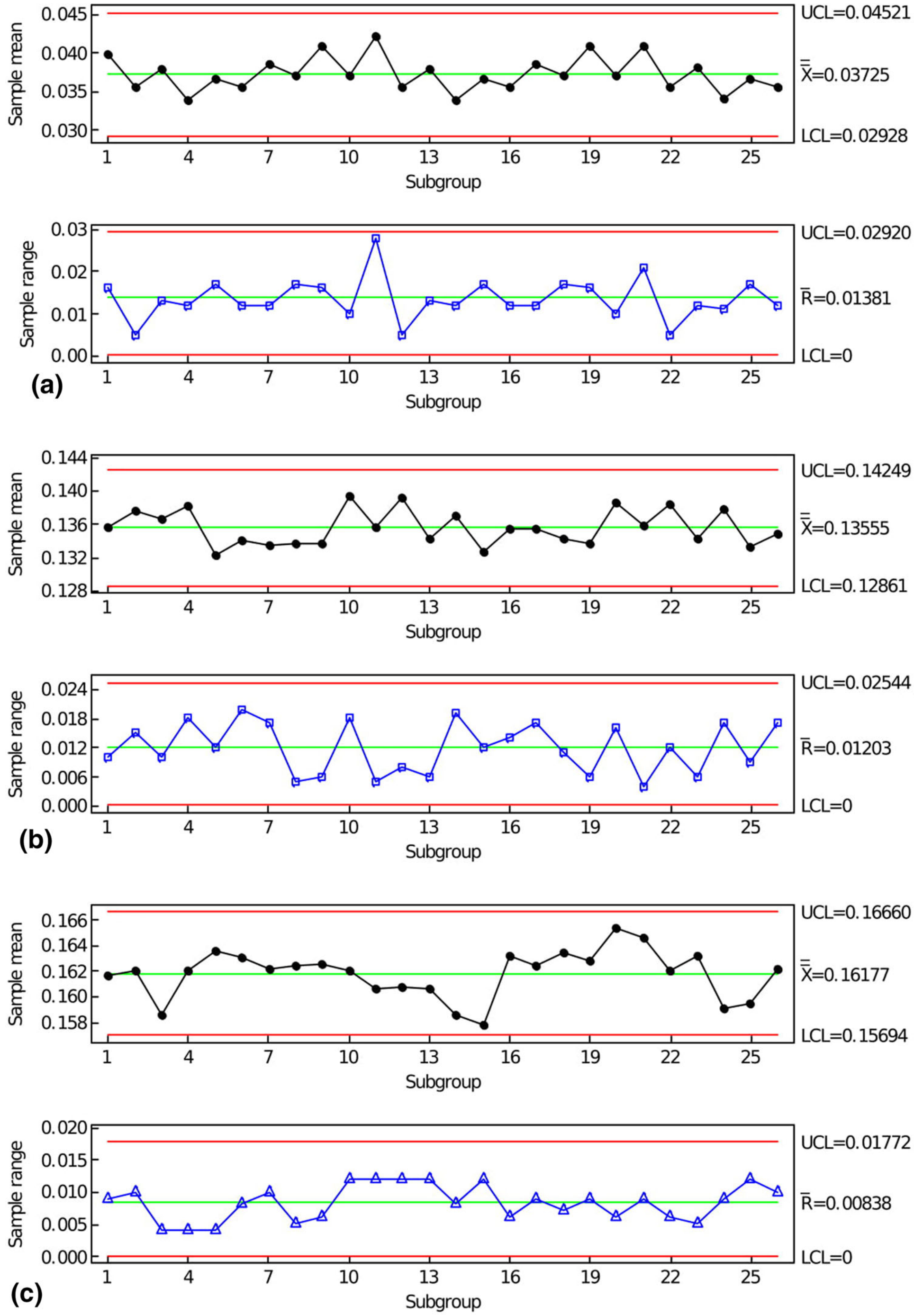

Fig. 4 $\bar{X}$ and R charts for EBH after drilling the (a) 2000th, (b) 10,000th and (c) 16,000th parts using an uncoated drill

values between using the uncoated and coated WC drills decrease gradually until reaching the 16,000th drilled parts. The variations of *Cpm* for all drills are not statistically significant after drilling the 16,001th and 22,000th drilled parts. It should be noted that the values of *Cpm* for the uncoated drills were not determined after drilling the 16,001th drilled part because the EBH was obviously larger than the customers' requirement.

Figure 12 presents the variation of percent part defects (*%def*) for EBH after drilling the forging brass workpieces using all drills. After drilling the 12,001th drilled part using the uncoated drills, *%def* increases by 10% with a high variation and then suddenly increases to 95% with a dramatically high number of defects at the 16,000th drilled part. On the other hand, the *%def* increase by the same rate with a moderate variation after drilling the 18,001th drilled part using the TiCN-coated WC drills before increasing instantaneously to approximately 90% with a smaller variation at the 22,000th drilled part. In addition, the variations of *%def* using the uncoated drills were higher than those using the TiCN-coated WC drills. Thus, drilling the workpieces using the TiCN-coated WC drills for 20,000 drilled parts will be better than that using the uncoated ones for 14,000 drilled parts. The percentage rate of part defects after drilling of the workpieces using the TiCN-coated WC drills for 20,000 drilled parts decreases by

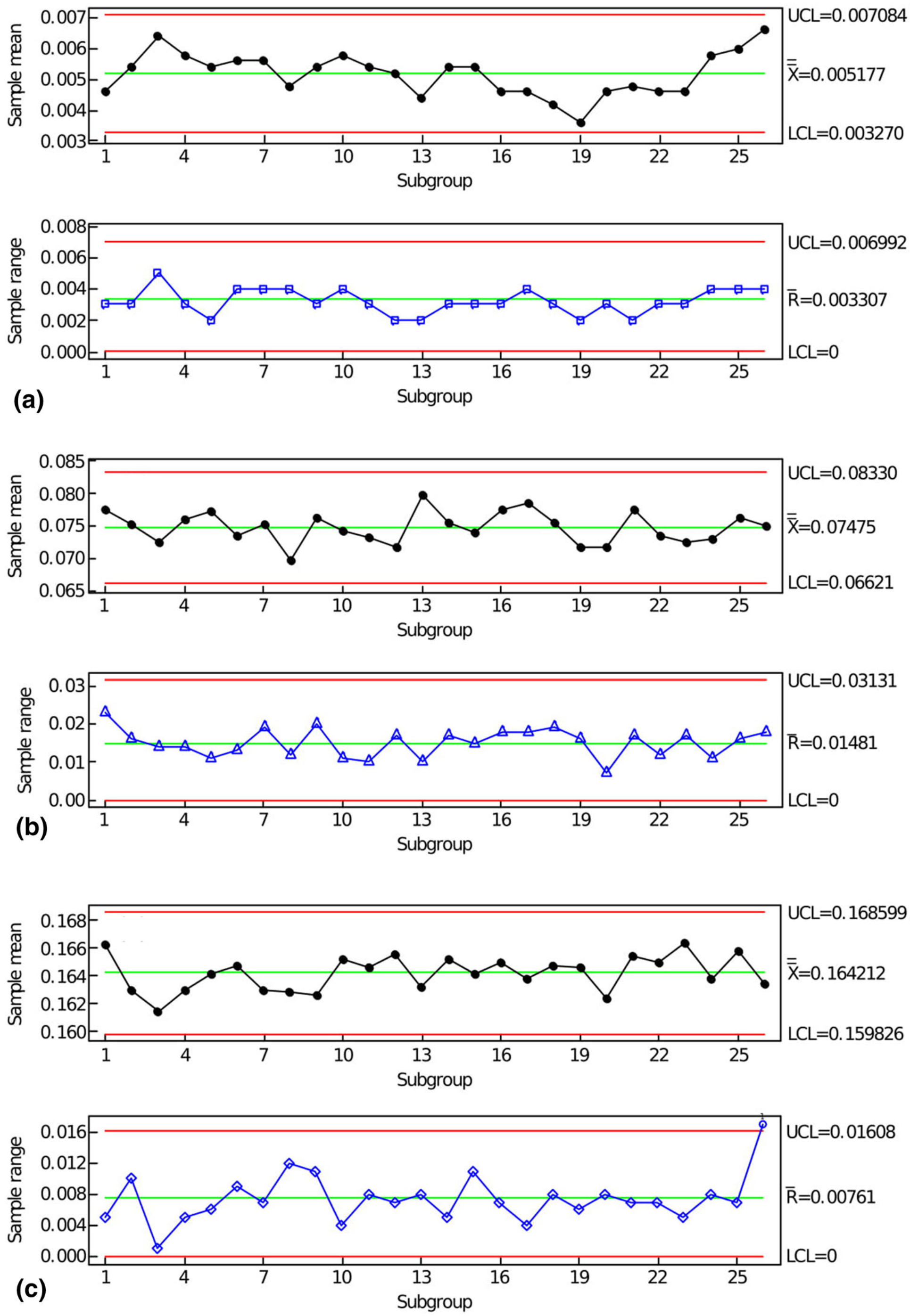

Fig. 5 $\bar{X}$ and R charts for EBH after drilling the (a) 2000th, (b) 10,000th and (c) 22,000th parts using a TiCN-coated WC drill

approximately 40% in comparison with that using the uncoated ones for 14,000 drilled parts.

The average values of %*def* using the AlCrN-coated WC drills were lower than those using the TiCN-coated ones. Consequently, there is a statistically significant difference of machining performance between the TiCN and the AlCrN-coated WC drills. Kalss et al. (Ref 8) reported that the tool life of AlCrN-coated solid carbide end mills was dramatically longer than that of the TiCN ones for milling of AISI 1045 carbon steel. The better performance of the AlCrN-coated WC drills could be attributed to the better oxidation resistance, lower thermal conductivity, friction coefficient and cutting forces leading to higher abrasive wear resistance (Ref 32). Theoretically, cutting forces are affected by cutting tool materials, machining conditions, workpiece materials, friction and plastic deformation. The reduction of plastic deformation and friction of chips moving along the rake surface will decrease thrust force and torque leading to the longer tool life (Ref 32). Hence the AlCrN-coated WC drills are suitable to drill the forging brass workpieces with relatively low values of EBH. Next, the effects of cutting speed and feed rate on average values of EBH, Ra and diameter would be investigated using design of experiments with ANOVA. In addition, appropriate operating conditions of drilling factors were

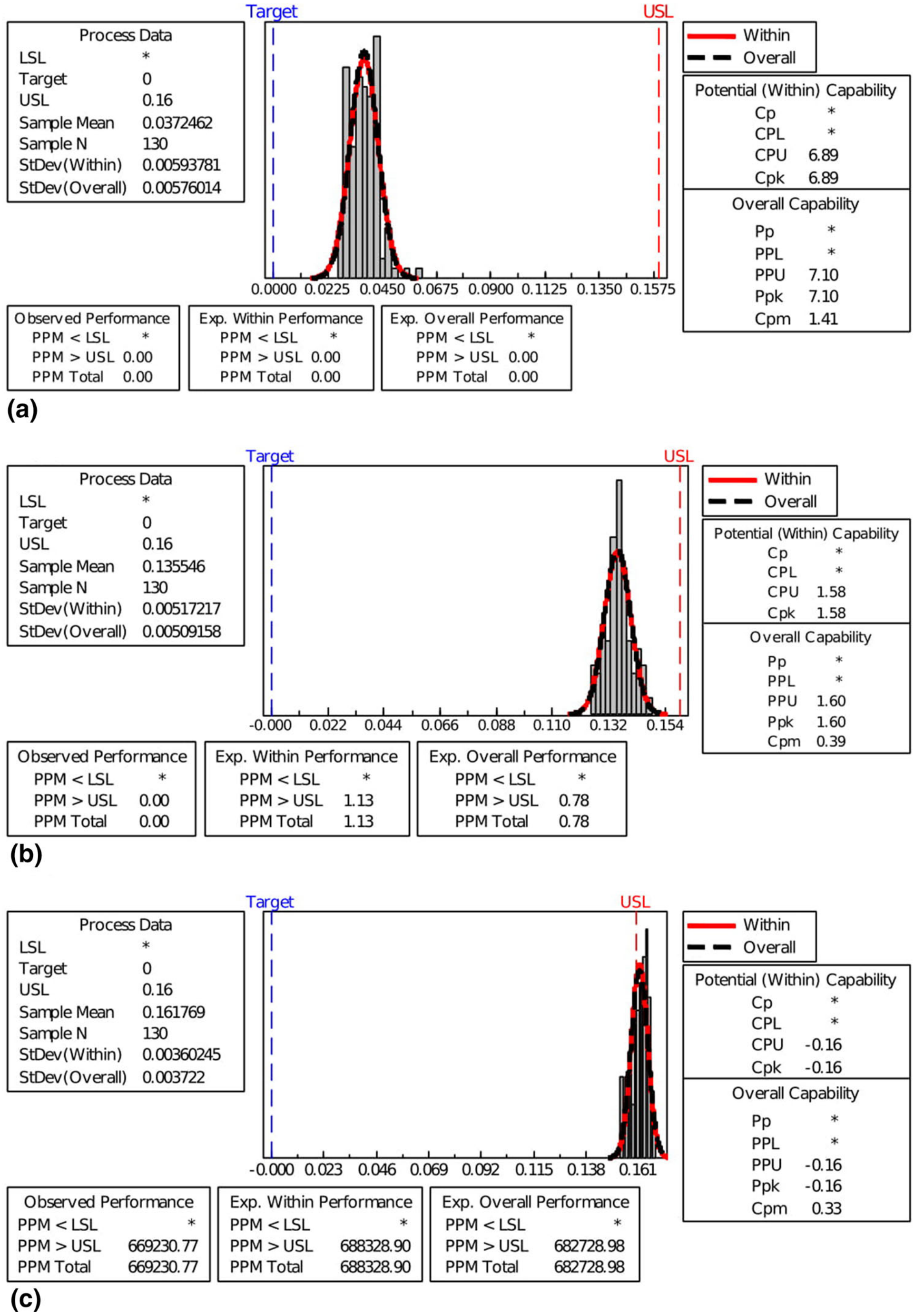

Fig. 6 Process capability output for EBH after drilling the (a) 2000th, (b) 10,000th and (c) 16,000th parts using an uncoated drill

evaluated by the method of RSM coupled with overlaid contour plot investigation.

3.3 Determining the Appropriate Operating Conditions

3.3.1 Design and Analysis of Experiments. Table 1 presents the drilling factors (cutting speed and feed rate) and their levels based on the sequential design of experiments (2^k factorial design and central composite design, CCD). The levels of each factor were represented by coded variables (− 1.414, − 1, 0, 1, and 1.414) and their corresponding actual variables. In the first step of the sequential design of experiments, 2^2 factorial design with one replication at each factorial points (− 1, − 1), (+ 1, − 1), (− 1, + 1) and (+ 1, + 1) and 4 replications at the center point (0, 0) were chosen to provide protection against curvature from second-order effects as well as allow an independent estimate of errors to be obtained.

Table 2 summarizes the ANOVA results for EBH, Ra and drilled diameter based on 2^2 factorial design and 4 replicates at the center point. Since the p values of curvature for all responses are smaller than the significance level of 0.05, there is an evidence of second-order curvature in each response over

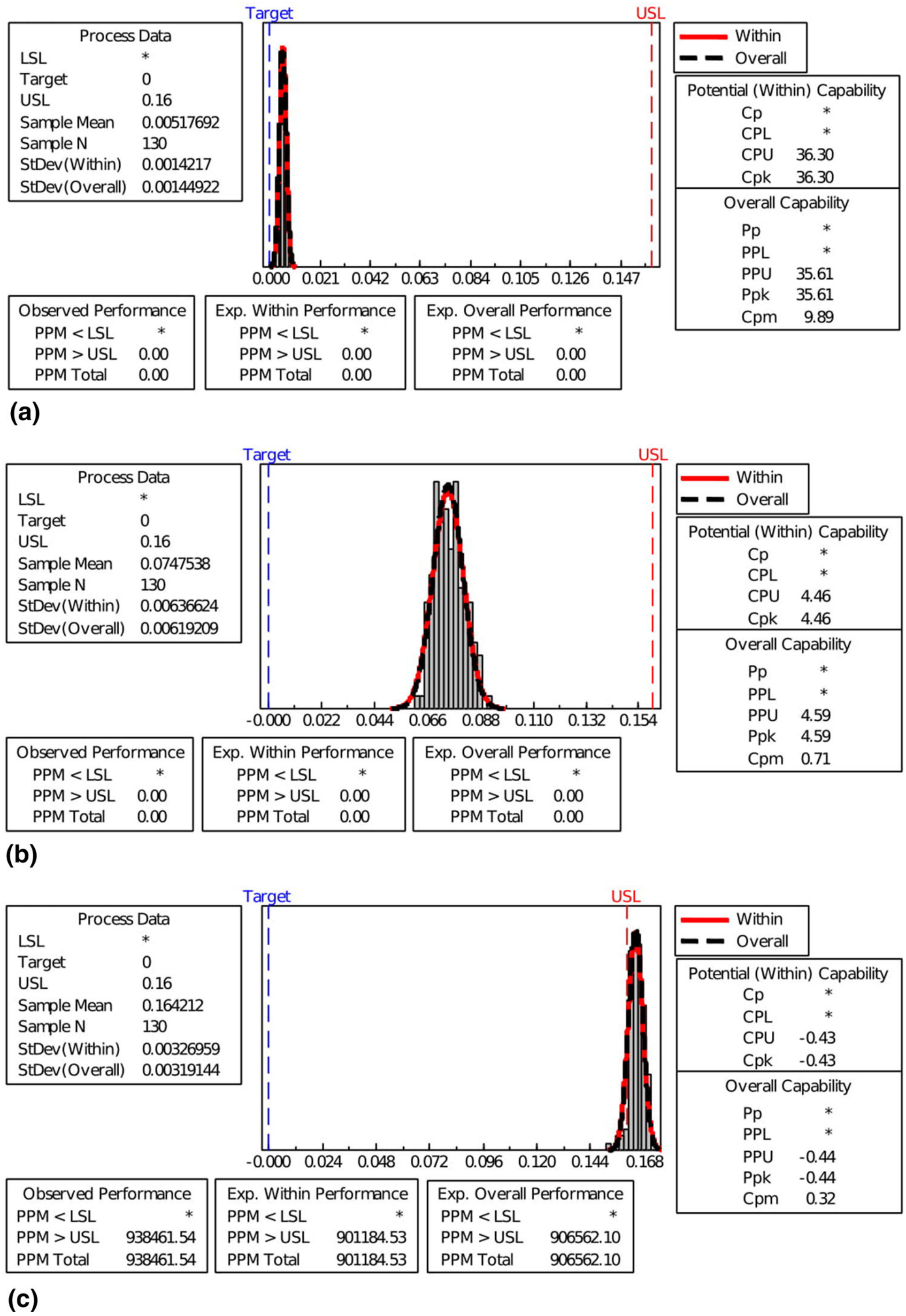

Fig. 7 Process capability output for EBH after drilling the (a) 2000th, (b) 10,000th and (c) 22,000th parts using a TiCN-coated WC drill

the region of exploration. The ANOVA results agree with those illustrated in Fig. 13, which indicate that the four observations at the center points lie away from each of the lines passing to the factorial points. Hence, additional analysis is needed to locate the appropriate operating conditions more precisely in the second step of the sequential experimental design. According to Table 1, four points designated as (1.414, 0), (− 1.414, 0), (0, 1.414) and (0, − 1.414) were added to augment the experimental design with enough points to fit the second-order models.

Models for predicting EBH, Ra and diameter values were developed based on experimental data sets from the first and the second steps of drilling tests. The coefficients involved in the three models were estimated by regression approach using the Minitab® software as shown in Table 3. The three models demonstrate that the values of $R^2 > 0.8$, which correspond to the ratio of the explained variation to the total variation and a measure of the degree of fit. It shall be noted that the adjusted R^2 excludes statistically insignificant factors. The values of adjusted R^2 is reasonable and the difference between the R^2 and

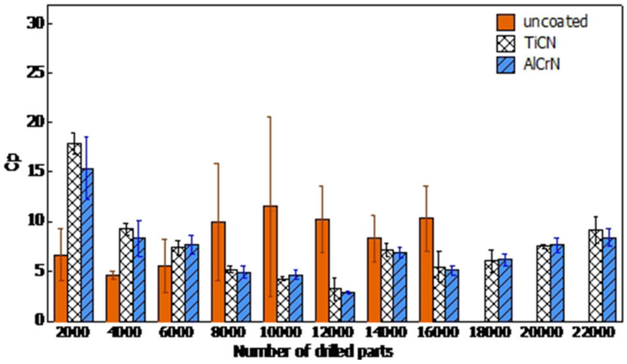

Fig. 8 *Cp* for EBH after drilling using the uncoated, TiCN- and AlCrN-coated WC drills

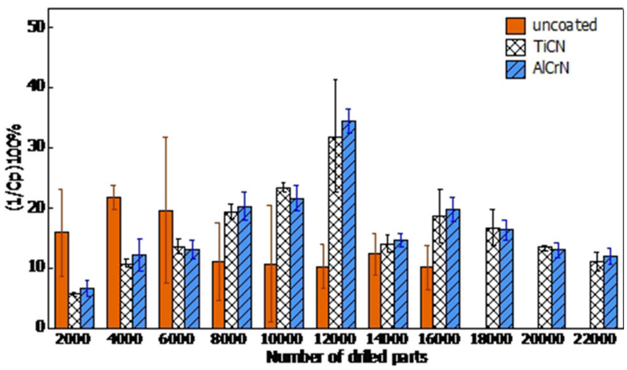

Fig. 9 (1/*Cp*)100% for EBH during drilling of the workpieces using the uncoated drills, TiCN- and AlCrN-coated WC drills

the adjusted R^2 is not very large. The results also dictate that the three models are adequate in predicting the behaviors of the EBH, Ra and diameter of drilled brass workpieces using the AlCrN-coated WC drills.

Figure 14 illustrates normality probability plots of standardized residuals for EBH, Ra and diameter values after conducting the CCD experiments. The three normality probability plots indicated that the plotted points approximately formed straight line and fell within the 95% confidence intervals (95% C.I.). This implied that residual analyses of these models were satisfactory based on the data sets of the EBH, Ra and diameter values.

Figure 15 shows the plots of the relationship between experimental observations and predicted values for the three responses. Generally, this plot is used to evaluate whether the developed model fits with the experimental observations (Ref 25). The plots for the three responses show that most experimental observations and predicted values move together along the same trends, indicating that the developed models fit well with the experimental observations for the three responses.

Figure 16, 17 and 18 depict the three-dimensional response surface plots and contour plots for the three responses in terms of cutting speed and feed rate obtained from the empirical models of EBH, Ra and drilled diameter in Table 3. According to Fig. 16, the value of EBH increases with increasing feed rate. It shall be noted that it is difficult to completely remove EBH in ductile materials such as copper and brass. Ahn and Lee (Ref 16) stated that ductility of materials could affect the

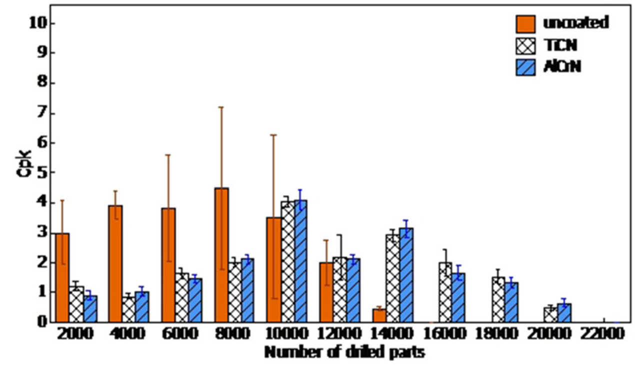

Fig. 10 *Cpk* for EBH during drilling of the workpieces using the uncoated, TiCN- and AlCrN-coated WC drills

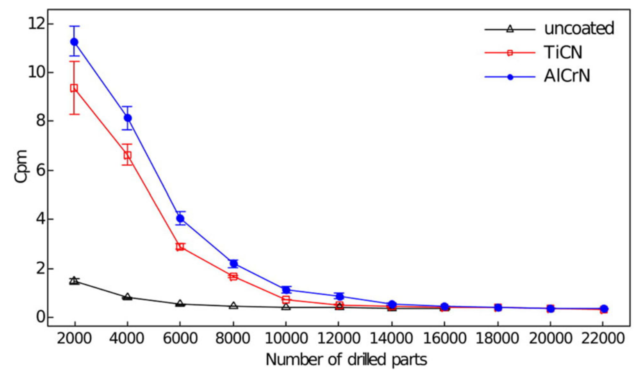

Fig. 11 *Cpm* for EBH during drilling of the workpieces using the uncoated, TiCN- and AlCrN-coated WC drills

average EBH value, which increased dramatically when drilling more ductile and softer materials with high feed rates. Similarly, Kamboj et al. (Ref 33) reported that thrust force and chip thickness increased when the feed rate increased leading to a large increase of EBH value after drilling Al6063/15%SiC composites with high speed steel step drills. Likewise, Yin et al. (Ref 34) investigated the effects of spindle speed and feed rate on thrust force and EBH in drilling of stacked Al-7475 sheets and observed that the EBH at lower and higher cutting speeds was relatively high compared with the intermediate level of the cutting speed but the EBH values were more sensitive to the change in feed rate than that in cutting speed.

Moreover, Fig. 17 shows that the value of Ra is more sensitive to the change in feed rate than that in cutting speed since Ra increases drastically with increasing feed rate. Similar influence of feed rate on Ra was reported by Meral et al. (Ref 35) in drilling of AISI 1050 steel using uncoated and other coating tools with comparable drilling conditions. This effect can be attributed to the fact that temperature increases at the contact area between the drill and workpiece. In addition, cutting chip flows easier and smoother due to low friction coefficient of the AlCrN coating material, resulting the decrease in thrust force that can lead to higher surface quality of the drilled parts.

According to Fig. 18, the diameter of drilled workpiece increases linearly with a decrease in cutting speed below 55 m/min and an increase in cutting speed above 65 m/min. In addition, the value of drilled hole diameter reaches the target value of 17.8 mm when drilling the workpieces at the cutting

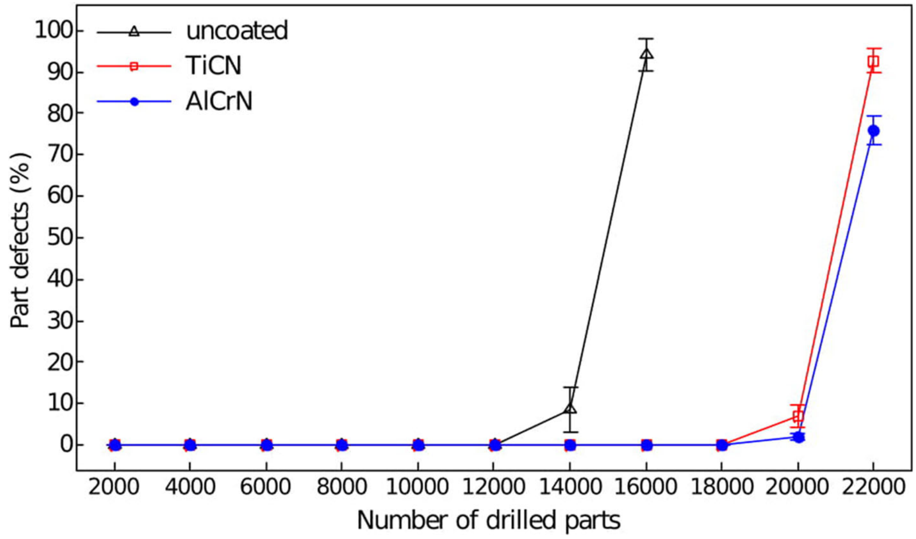

Fig. 12 Percent part defects for EBH during drilling of the workpieces using the uncoated, TiCN- and AlCrN-coated drills

Table 1 Drilling factors and their levels

	Levels				
Factor	− 1.414	− 1	0	1	1.414
Cutting speed (m/min)	46	50	60	70	74
Feed rate (mm/rev)	0.17	0.18	0.20	0.22	0.23

speed of approximately 55 m/min with varying feed rates in the range of 0.19-0.21 mm/rev. Furthermore, the response diameter is more sensitive to the change in cutting speed than to that in feed rate.

The results from response surface plots and contour plots for the three responses indicate that the conflict between the two factors on the appropriate operating conditions arises and the appropriate operating conditions of the two factors may occur within the ranges of the two factors. Thus, additional sensitivity analysis is needed.

3.3.2 Sensitivity Analysis. In order to achieve minimum EBH, Ra and deviation of drilled hole diameter relative to the target value of 17.8 mm, the appropriate operating conditions of the process factors can be determined using sensitivity analysis based on overlaid contour plot approach. This approach is a graphical optimization, in which multiple responses simultaneously meet the proposed criteria by superimposing or overlaying criteria response contours on the same plot (Ref 25). The overlaid contour plots were employed to investigate the sensitivity of cutting speed and feed rate on the three responses simultaneously.

Since EBH and diameter of drilled holes are critical responses in this study, the value of EBH should be reduced as much as possible. The target diameter of drilled hole was 17.8 mm. The value of Ra was set within the specifications of 2-3 μm based on customers' requirement. Figure 19 illustrates the overlaid contour plots of EBH, Ra and diameter after drilling forging brass workpieces using AlCrN-coated WC drills with different cutting speeds and feed rates with respect to the constraints of 0.151 mm $<$ EBH $<$ 0.1535 mm, 2 μm $<$ Ra $<$ 3 μm and 17.785 mm $<$ diameter $<$ 17.8 mm. The shaded areas of the plots are the regions that do not meet the selection criteria of the three responses. On the other hand, the unshaded areas correspond to the feasible operating conditions of the drilling factors including cutting speed and feed rate that can simultaneously meet the critical requirements. The desired values of EBH, Ra and diameter can be obtained at any combinations within the feasible regions. It can also be observed from these plots that the EBH increases with increasing feed rate and the sensitivity on EBH of feed rate is relatively high compared with that of cutting speed.

To meet the Ra value within the range of 2 and 3 μm, feed rate was set to be at most 0.19 mm/rev. Similarly, cutting speed was set to be at least 55 m/min to meet the target diameter of 17.8 mm. Meanwhile, feed rate and cutting speed were set to be at least 0.17 mm/rev and at most 57 m/min in order to keep the values of EBH, Ra and diameter at least 0.152 mm, 2 μm and 17.79 mm, respectively. Hence, the appropriate operating conditions including cutting speeds ranging from 55 to 57 m/min and feed rates ranging from 0.17 to 0.19 mm/rev provided the EBH values, roughness (Ra) and diameters in the ranges of 0.152-0.1535 mm, 2-3 μm and 17.79-17.8 mm, respectively.

4. Conclusions

The machining performances of uncoated, TiCN- and AlCrN-coated WC drills during drilling of forging brass were achieved by performing the basic process capability analysis based on the data set of the exit burr height values as the function of the number of drilled parts used for producing the water-valve components. The process capability indices could successfully apply to monitor the number of drilled parts of the drilling process. The values of *Cp*, *Cpk*, *Cpm* and (1/*Cp*)% were employed to monitor and reveal the machining capability for different numbers of drilled parts.

Table 2 ANOVA results for EBH, Ra and drilled diameter based on 2^2 factorial design and 4 replications at the center point

		EBH		Ra		Diameter	
Source of variation	***df***	**SS**	***p* value**	**SS**	***p* value**	**SS**	***p* value**
Model	3	3.733×10^{-5}	< 0.0001*	1.720	0.0003*	2.207×10^{-3}	0.0221*
A-Cutting speed	1	4.203×10^{-6}	0.0005*	0.016	0.0527	1.892×10^{-3}	0.0071*
B-Feed rate	1	2.970×10^{-5}	< 0.0001*	1.697	< 0.0001*	4.225×10^{-5}	0.3974
AB	1	3.422×10^{-6}	0.0007*	5.852×10^{-3}	0.1539	2.723×10^{-4}	0.0878
Curvature	1	1.128×10^{-5}	0.0001*	0.048	0.0123*	1.352×10^{-3}	0.0114*
Pure error	3	5.000×10^{-8}		4.874×10^{-3}		1.308×10^{-4}	
Total	7	4.866×10^{-5}		1.771		3.689×10^{-3}	

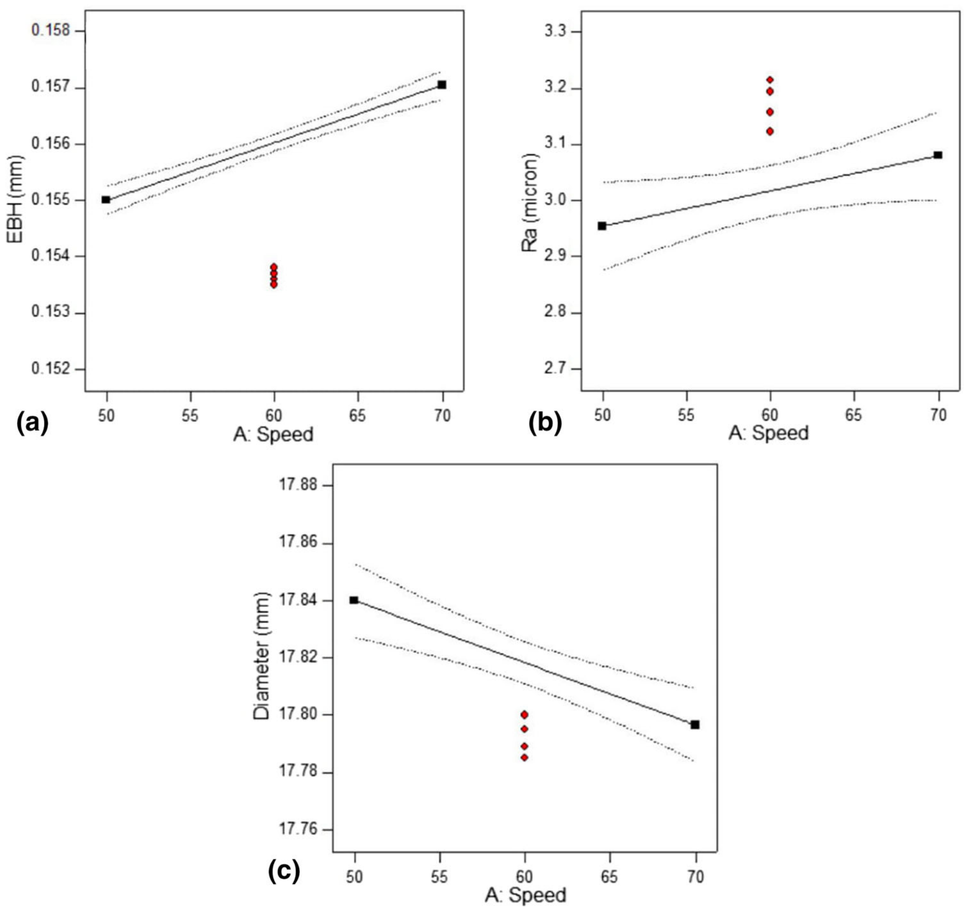

Fig. 13 Main factorial plot with four observations at the center point for EBH, Ra and diameter

Table 3 Empirical model results for EBH, Ra and drilled diameter based on CCD

	Coefficient estimated		
Factorial effect	**EBH**	**Ra**	**Diameter**
Intercept	0.15	3.16	17.79
A-Cutting speed	9.721×10^{-4}	0.059	− 0.013
B-Feed rate	1.345×10^{-3}	0.51	0.00463
AB	9.250×10^{-4}	− 0.038	0.00825
A^2	2.575×10^{-3}	0.18	0.025
B^2		− 0.23	
R^2	0.8197	0.9280	0.8589
Adj R^2	0.7395	0.8829	0.7962

The findings on the machining performances of the three types of drills could be summarized as follows:

- The average EBH for uncoated, TiCN- and AlCrN-coated WC drills was significantly different from each other ranging from 0.03 to 0.1 mm before reaching the criterion of EBH of 0.16 mm.
- The *Cpm* index was suitable to monitor the machining capability related to the process target for EBH criterion of 0.16 mm during drilling of the workpieces using both coated drills.
- The values of *Cpm* for the uncoated drills were not determined after drilling the 16,001th drilled part in agreement

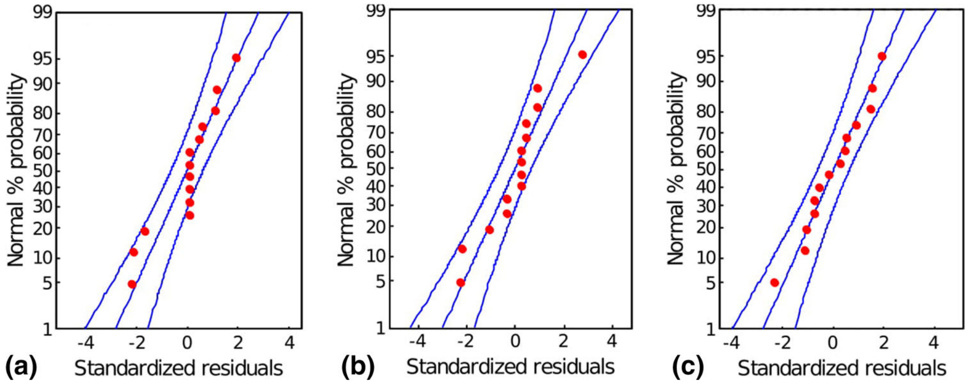

Fig. 14 Normality probability plots of standardized residuals for (a) EBH, (b) Ra and (c) diameter

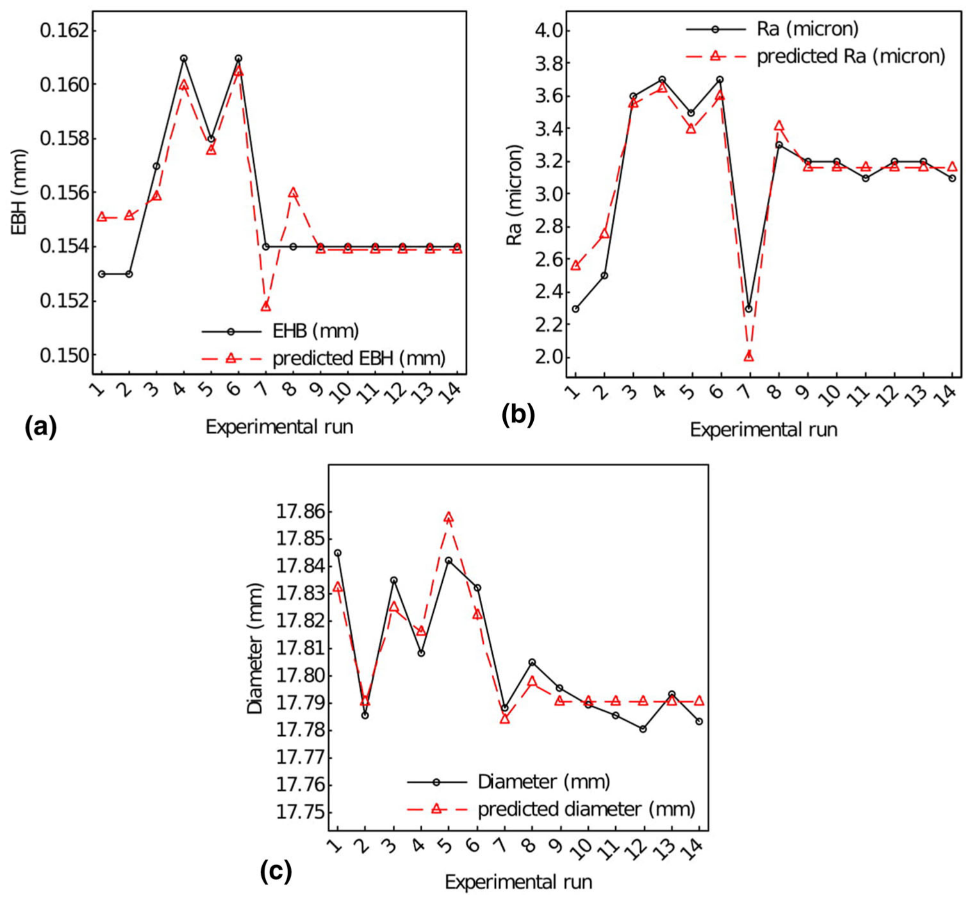

Fig. 15 Plots of experimental observations and predicted values for (a) EBH, (b) Ra and (c) diameter

with the results of the variation of EBH versus the number of drilled parts.

- The machining performances of the AlCrN-coated WC drill were better than those of the uncoated and TiCN-coated ones based on the EBH criterion of 0.16 mm and the variations of the drilling machining capability indices.
- The appropriate operating conditions including cutting speeds ranging from 55 to 57 m/min and feed rates ranging from 0.17 to 0.19 mm/rev during drilling of the workpieces with the AlCrN-coated WC drills were determined using CCD, ANOVA and RSM coupled with overlaid contour plot investigation and sensitivity analysis.

Further to the research, there should be future studies of more advanced coatings and the determinations of appropriate operating conditions in order to enhance the performances and productivity of drilling processes for various kinds of workpiece materials.

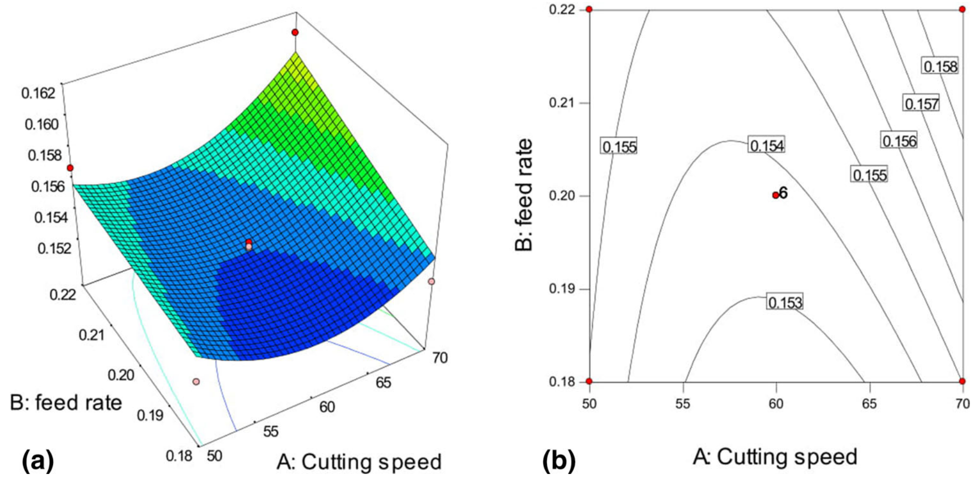

Fig. 16 Response surface and contour plots of the EBH response

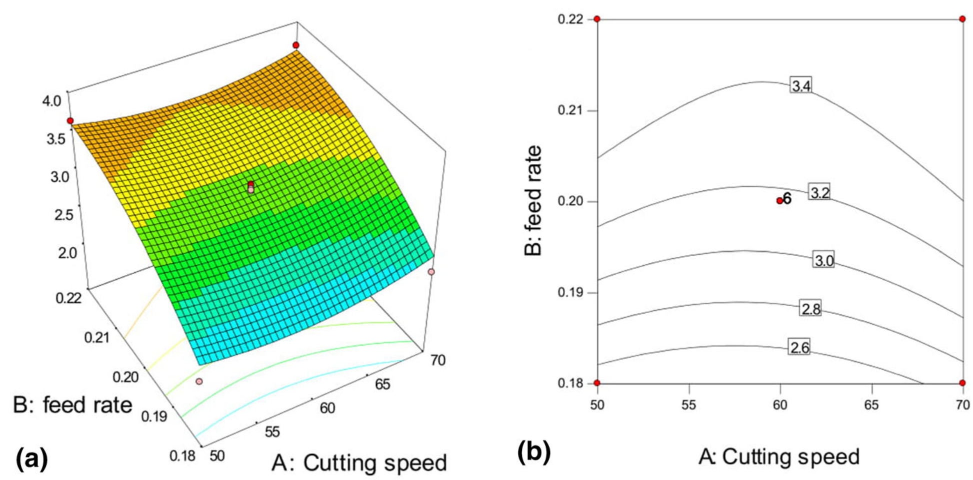

Fig. 17 Response surface and contour plots of the Ra response

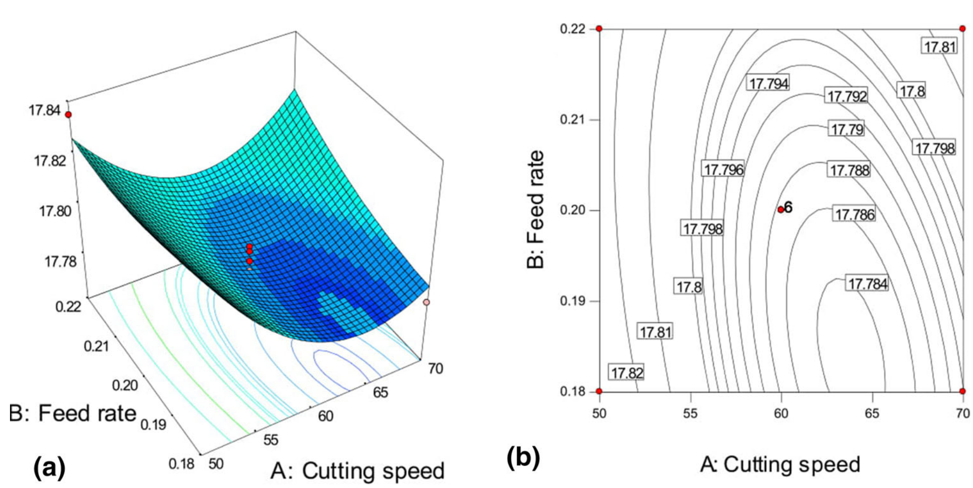

Fig. 18 Response surface and contour plots of the diameter response

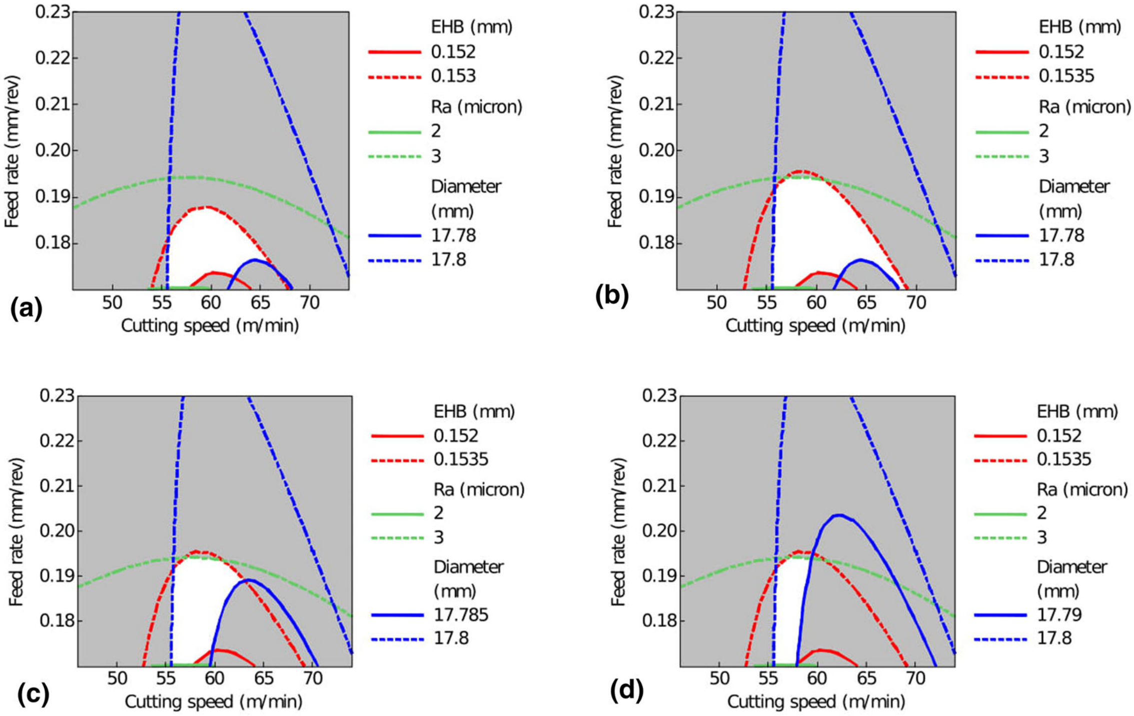

Fig. 19 Overlaid contour plots of EBH, Ra and diameter with different cutting speeds and feed rates

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