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DESIGN AND MACHINING OF COPPER SPECIMENS WITH MICRO HOLES FOR ACCURATE HEAT TRANSFER MEASUREMENTS

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This article presents a technique that has been developed specifically for drilling 0.5334-mm-diameter, 19-mm-deep holes in copper for use in temperature measurement. The holes accept thermocouples, which are used for the measurement of the temperature gradient and the wall temperature of the specimen. Errors due to the intrusion of the probe, and the finite size and mass of the probe, are reduced as the diameter of the probes is reduced. A machining procedure for drilling deep micro holes in copper cannot be found in conventional texts; this article advocates holes that are deeper than those traditionally recommended. This article is written for both machinists and experimentalists. Both heat transfer and machining criteria are considered. The necessary equipment and their specifications are discussed. Special attention is given to specifying drilling speeds, feed rates, and lubricants. Step-by-step drilling instructions are given. An analysis is performed to reveal the important parameters for reducing the errors associated with the uncertainty in the location, the relative position of the thermocouples, and the individual temperature measurements.

As enhanced heat transfer surfaces become increasingly efficient, the corresponding driving temperature differences become smaller. Consequently, the accuracy of the temperature difference measurement must be increased to maintain the same accuracy for the calculation of the heat transfer coefficient. Wilcox and Rohsenow [1] and Kedzierski and Webb [2] utilized thick heat transfer surfaces with thermocouples embedded along the line of the heat flux to improve the accuracy of the heat transfer coefficient measurement. Figure 1 shows an example of a heat transfer test specimen with three sets of four thermocouples aligned

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NOMENCLATURE

D	diameter of drill or hole, m
e	error in the measurement of individual temperature, K
E_g	error in dT/dx for 99.7% confidence, K
$\%E_g$	percent error in temperature gradient calculation, K
E_r	ratio of position errors to temperature errors
E_{Ti}	error in T measurement for 99.7% confidence, K
E_{Tw}	error in the T_w calculation for 99.7% confidence, K
$f(x)$	Gaussian density function
k	thermal conductivity of test specimen, W/m K
N	number of thermocouple holes aligned with heat flux direction
q''	heat flux, W/m^2
s	estimated standard deviation
s_q	estimated standard deviation of q'' calculation, W/m^2
s_{Ti}	estimated standard deviation of individual T measurement, K
s_{Tw}	estimated standard deviation of T_w calculation, K
s_x	estimated standard deviation of thermocouple location, m
s_ϵ	estimated standard deviation of total measurement error, K
S	cutting speed of drill, m/s
t	thickness of test specimen; see Fig. 1, m
T	measured temperature, K
T_w	Temperature of heat transfer surface, K
V	angular speed of drill, rpm
x	coordinate for thermocouple location, m
$\bar{x}$	arithmetic mean of N values of x, m
δ	error in position measurement, m
ϵ	total measurement error in Eq. (1), K

Subscript

i	hole number increasing with]] increasing x

perpendicular to the heat transfer surface. Thermocouples embedded in a test specimen are used to simultaneously measure the temperature gradient and to extrapolate the surface temperature. The temperature gradient is used to calculate the heat flux. The surface temperature is used to calculate the driving temperature difference.

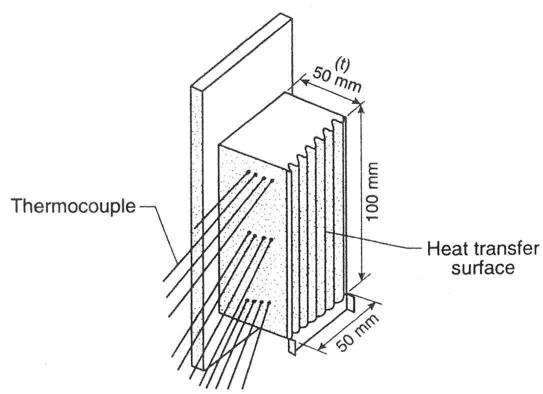

Figure 1. Sample copper heat transfer specimen.

The calculations of the heat flux and the wall temperature rely on an accurate value for the thermal conductivity of the metal. Pure, 100% oxygen-free copper is used as a heat transfer specimen because its thermal conductivity is accurately known. A metal alloy is less desirable for test specimens due to the variation of thermal conductivity with composition. Deviation of the actual composition from the nominal composition may be enough to place significant uncertainty in the property values. Consequently, an additional expense must be borne to measure the thermal conductivity of an alloy.

Another reason for the use of copper as a heat transfer specimen is that its thermal conductivity is nearly constant throughout a test block for a wide range of heat fluxes. The temperature profile within the block is assumed to be linear for the calculation of both the heat flux and the surface temperature. If the thermal conductivity varies within the block, the slope of the temperature profile will vary. The small temperature gradient present in copper provides for a nearly constant thermal conductivity. Consequently, the assumption of a linear temperature profile can be met with a copper test block.

Instrumentation of the heat transfer block can be designed to minimize errors associated with the heat transfer measurement. Small-diameter thermocouples can be used to lessen the errors associated with the intrusion of the probe into the medium and the errors due to the finite size and mass of the probe. For example, the disturbance of the isotherms of the test specimen, caused by the intrusion of the thermocouple, is diminished by reducing the diameter of the thermocouple. Likewise, the reduction in the size and the mass of the probe leads to a smaller uncertainty in the position of the thermocouple and a smaller error due to fluctuations from steady state, respectively. The Design section of this article demonstrates that use of 0.5334-mm-diameter holes results in a relatively small uncertainty in the hole position. The analysis also shows that minimizing errors due to the uncertainty in the thermocouple location is essential. These errors can be greater than those due to the accuracy of the temperature measurement. Wilcox and Rohsenow [1] specify that block materials with high thermal conductivities can be used to further reduce the measurement errors. Measurement errors that are due to conduction along the thermocouple leads can be reduced by providing for a sufficient immersion depth [3]. Consequently, the use of small, deep-well thermocouples in a highly thermally conductive material, such as copper, constitutes an experiment that yields highly accurate heat transfer coefficients.

Small-diameter holes may be produced by many methods. Electron beam machining (EBM), electrical discharge machining (EDM), laser beam machining (LBM), plasma beam machining (PBM), and ultrasonic machining (UM) are a few of the nontraditional machining methods for producing holes. The practical applications of these methods to hole making are discussed in *Thermal Machining Processes* [4] and Markov [5]. The above methods are expensive compared to traditional drilling. Also, some of the methods are limited by the depth of holes that can be achieved or the conductivity and hardness of the workpiece. If machining cost is a limiting factor, then traditional drilling may be the logical alternative to the nontraditional methods.

The gummy, soft nature of pure copper causes difficulty when machining tiny, deep holes. On occasion, the copper seems to grab and break the drill bit. Unfortunately, the broken drill bit always remains lodged within the copper. Electrical discharge machining can be used to remove the broken bit, but this method is too expensive and time consuming to be used to produce the holes. As a result, many good machinists do not attempt to drill micro holes in copper. Based on personal experience, the authors want to provide guidance to those machinists and experimentalists who wish to machine micro holes in copper.

Yee and Blomquist [6] have developed an automatic hole-drilling apparatus that detects tool wear to replace the drill bit before it fails. The on-line system has been used to drill 1-mm-diameter holes in 6.4-mm mild steel plate. It might be possible to adapt the system for drilling smaller-diameter and deeper holes in copper. Unfortunately, the on-line drilling system is not available commercially. Consequently, it may require considerable effort to procure such an apparatus and then tailor it to a specific application.

Regardless of the method used to produce the hole, the designer must consider the parameters that may be used to minimize measurement errors. The following test overviews the key parameters in the design of solid heat transfer specimens for accurate heat transfer measurements.

DESIGN OF HEAT TRANSFER SPECIMEN

Following is an analysis of the errors caused by the uncertainty in the position of the temperature measurement within a hole and the uncertainty in the temperature measurement itself. The pertinent errors are those found in the calculation of the heat flux and the temperature gradient. Since these calculations require more than one hole, the hole pattern also affects the calculation errors. Hence, three different hole patterns were investigated in order to determine that influence on the errors. This study is done to determine the important factors to consider in designing a heat transfer specimen to minimize the errors resulting from the uncertainty in the location of the thermocouple within the hole, the arrangement of the holes, and the individual temperature measurement.

The analysis was conducted using six assumptions: (1) The errors are random, independent, and exhibit a constant standard deviation; (2) the measurements are normally distributed about a mean value; (3) the temperature is associated with a point and not an area; (4) the intrusion of the thermocouple does not alter the temperature profile; (5) the thermal conductivity of the block is constant throughout; and (6) the heat flux is one-dimensional in the x direction within the region of the thermocouples and the position of T_w. The first two assumptions are required in order to perform a least-squares regression of the temperature on the thermocouple position. Assumption 2 is necessary to construct confidence intervals. The effect of a temperature pertaining to an area, not a point, may be considered to have the same effect as an uncertainty in the position of the thermocouple. Assumptions 3, 4, and 5 are satisfied for a thermocouple hole of zero diameter and an infinitely thermally conductive material, respectively. For hole diameters larger than some value, the errors due to disturbed isotherms will be greater than those due to the uncertainty in the location of the thermocouple. Assumption 6 is true for a flat surface with insulated sides and a uniform condition at the heat transfer surface. Errors introduced by an inherent nonuniform heat flux at the surface of some enhanced geometries should be small if the wall temperature is taken as the temperature just below the structure of the enhancement.

Since the thermal conductivity (k) of the block is constant and the conduction is one-dimensional, the functional relationship between temperature (T_i) and position (x_i) is linear:

$$T_i = T_w - \frac{q''}{k} x_i + \left(e_i + \frac{q''}{k} \delta_i \right) \tag{1}$$

The T_i is the measured temperature at position i. Let ϵ_i be the total measurement error, where $\epsilon_i = e_i + q'' \delta_i / k$. Figure 2 shows the coordinate system with the measured hole positions x_i, where $i = 1$ through 4. The error in the measurement of the temperature T_i is e_i, or E_{Ti} for a 99.7% confidence interval. The error in the measurement of the position x_i is δ_i. The wall temperature (T_w) and the temperature gradient (dT/dx) are estimated by a linear least-squares fit of the measured temperatures versus the thermocouple locations. The intercept of the fit is T_w when the heat transfer surface is taken as $x = 0$. The slope of the fit is equal to the temperature gradient.

A linear least-squares regression of T_i on x_i is valid if x_i has been measured with no error. Bartlett [7] has developed a modification of the least-squares method in order to fit a straight line to variables that are both subject to error. Berkson [8] has shown that this special procedure is not necessary if the independent variable is a "controlled" observation. The "controlled" observation for the present situation is the position of the thermocouple holes. The hole position has been preselected and premeasured. The temperature measurement is assumed to be located at the center of the hole. However, the actual location of the thermocouple is different from the location of the hole and is unknown. Hence, the error in the position of the thermocouple is the distance between the center of the hole and the actual position of the thermocouple within the hole.

Following is an argument for an estimate of the standard deviation of the position of the thermocouple from the center of the hole. There is a 100%

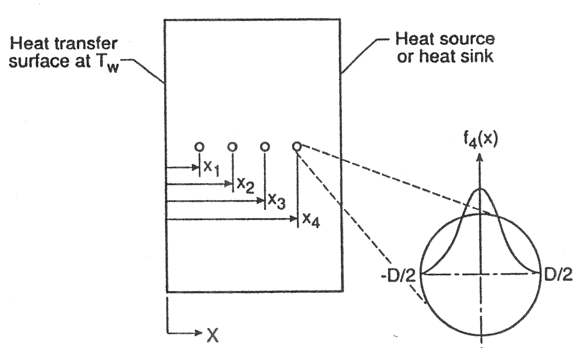

Figure 2. Coordinate system for thermocouple holes.

probability that the measured temperature is for some position within the hole. The center of the hole is the single most probable position; it is assumed to be equal to the mean value. If a normal distribution of possible positions $[f(x)]$ is fitted within the hole, as shown in Figure 2, then 99.7% of all the positions fall within 3 standard deviations of the mean value. Consequently, there are approximately 6 standard deviations of probable thermocouple locations for a given hole diameter. Hence, 1 standard deviation for the position within a hole (s_x) of diameter D can be estimated:

$$s_x = s_\delta = \frac{D}{6} \tag{2}$$

The s_x and s_{Ti} are now combined to estimate 1 standard deviation of the total measurement error associated with Eq. (1) (ϵ_i) as:

$$s_\epsilon = \sqrt{s_{T_i}^2 + \left(\frac{q'' D}{6k}\right)^2} \tag{3}$$

Error Ratio

The error ratio (E_r) is a convenient dimensionless constant that can be used to determine the relative contributions of the uncertainties of the individual temperatures and positions to the errors in the q'' and T_w calculations; i.e.,

$$E_r = \frac{q'' D}{6ks_{T_i}} \tag{4}$$

For E_r equal to 0.5, elimination of the entire position uncertainties would result in a 10% reduction of the errors in the q'' and T_w calculations. For values of E_r less than 0.5, the influence of the position uncertainty becomes less and the total error is dominated by the uncertainty in the individual temperature measurements. This region is the temperature-sensitive region. For example, the hole position uncertainties contribute approximately 1% to the total error in the heat flux and wall temperature calculations for an error ratio equal to 0.14. For values of E_r greater than 2, the total error is predominantly a consequence of the position errors; this is the position-sensitive region. For E_r equal to 2, elimination of the entire temperature measurement uncertainties would reduce the errors in the q'' and T_w calculations by only 10%. It follows that both position errors and errors in the temperature measurements contribute to the total error for values of E_r that are between 0.5 and 2. Reduction in either position or temperature measurement uncertainties act to reduce the total error in this transition region.

An error ratio of 0.14 should be used as an aid in the selection of the hole diameter that, if used, will nearly eliminate the errors due to the uncertainties in hole position. A conservative design would be one that was done for the largest expected heat flux. For example, if the thermocouples have been calibrated to within ± 0.2 K and it is planned to use a copper specimen with a maximum heat flux of 50 kW/m^2, setting E_r equal to 0.14 in Eq. (4) results in a hole diameter of approximately 0.44 mm. A value of $E_r = 0.14$ ensures that the errors in the q'' and the T_w calculations are minimized to within 1% of the minimum error for a particular temperature measurement uncertainty.

Wall Temperature Uncertainty

Ku [9] presents equations for the standard deviations of the slope and the intercept of linearly fitted y_i versus x_i data as functions of x_i and the standard deviation of y_i from the fitted line. Here, the x_is are the various distances of the thermcouple locations measured from the heat transfer surface. The y_is are the measured temperatures at the respective x_i locations. The equations for the standard deviation of the wall temperature and the standard deviation of the temperature gradient are obtained by substituting Eq. (2) into the relationships given by Ku [9]. This substitution can be rearranged to provide an estimate of the ratio of the standard deviation in the estimated wall temperature (s_{Tw}) due to the uncertainties in thermocouple location and temperature measurements to the standard deviation of the individual temperature measurements (s_{Ti}):

$$\frac{s_{T_w}}{s_{T_i}} = \sqrt{1 + \left(\frac{q''D}{6ks_{T_i}}\right)^2} \sqrt{\frac{1}{N} + \frac{\bar{x}^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2}} \tag{5}$$

Equation (5) shows that errors in the calculation of T_w are governed by five parameters: (1) the error in the temperature measurement, (2) the magnitude of the heat flux, (3) the diameter of the hole, (4) the thermal conductivity of the block, and (5) the arrangement and number of the thermocouple holes. Errors in the calculation of the wall temperature can be minimized by designing the test specimen to have a large thermal conductivity, and a large number of widely spaced small diameter holes. Also, thermocouples spaced more closely to the heat transfer surface will reduce the arithmetic mean of x ($\bar{x}$), which will give a smaller s_{Tw}/s_{Ti} ratio. Increasing the error in the temperature measurement may reduce the s_{Tw}/s_{Ti} ratio, but it thwarts the quest for accuracy by also increasing the magnitude of s_{Tw}.

Figure 3 presents Eq. (5) graphically in order to illustrate the influence of the number and the arrangement of the holes on the error associated with the calculation of the wall temperature. The ordinate is the ratio of the error in the wall temperature calculation (E_{Tw}) to the error in the hole temperature measurement (E_{Ti}) for 99.7% uncertainty. The abscissa is the number of thermocouple holes (N) placed in a row perpendicular to the heat transfer surface. The effects of three different hole arrangements were investigated: (1) holes evenly spaced as defined by $x_i = it/(N+1)$, (2) holes concentrated near $x = 0$ (near T_w) as defined by $x_i = t/(N+1)!\Sigma i$, and (3) holes concentrated near $x = t$ as defined by $x_i = t - t/(N+1)!\Sigma i$. The illustration is for $E_r = 0.2$ and a block thickness (t) of

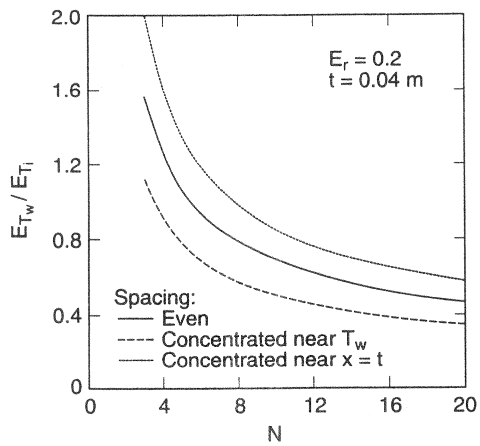

Figure 3. Effect of the number and arrangement of thermocouples on the accuracy of the wall temperature calculation.

0.04 m. In general, the E_{Tw}/E_{Ti} ratio diminishes for increasing N and is small, having the value of approximately 1.2 for four evenly spaced holes. The accuracy of the calculated wall temperature can actually be greater than the accuracy of the individual temperature measurements that were used to calculate the wall temperature. In fact, the E_{Tw}/E_{Ti} ratio is less than 1 for N evenly spaced holes greater than 5. For example, an error in the wall temperature calculation for 20 thermocouple holes is 50% less than the error in the individual temperature measurement. A heat transfer specimen with 20 thermocouples represents an extraordinary effort that may not be justified by the additional accuracy.

Figure 3 illustrates that the error ratio for thermocouples spaced closely to $x = t$ is approximately 26% greater than that for evenly spaced thermocouples. The error ratio for thermocouples spaced closely to the heat transfer surface is approximately 27% less than that for evenly spaced thermocouples. Concerns about errors due to disturbed isotherms may override the temptation to place the thermocouples closer to the heat transfer surface. The temperature disruptions produced by each hole may interact and cause significant deviation of the temperature profile from a linear one. The improvement in the accuracy of the wall temperature calculation for thermocouples spaced closer to the heat transfer surface (hole arrangement #2) is approximately 0.06 K, which is relatively inconsequential. Therefore, the increased accuracy is not worth achieving, because the hole arrangement may cause greater errors due to the disturbed isotherms. Wilcox and Rohsenow [1] have suggested assuming that the hole diameter is twice its actual value to conservatively approximate the error due to disturbed isotherms. However, more information on the effect of the hole on the temperature profile is required before a densely packed hole pattern can be considered. Thus, the authors recommend that the thermocouples be evenly spaced in order to avoid compounding the errors associated with altered isotherms.

Figure 4 shows the effect of the temperature gradient on the uncertainty of the wall temperature calculation for a 0.04-m-thick specimen with four aligned thermocouple holes. The error in the wall temperature calculation increases for increasing heat flux for the three different hole arrangements presented. The temperature-sensitive, the transition, and the position-sensitive regions are depicted in the figure. The position-sensitive region encompasses temperature gradients that are greater than 1550 K/m. The temperature-sensitive region exists for temperature gradients below 360 K/m. The E_{Ti} calculated from the condensation data of Kedzierski and Webb [2] are also presented on the graph. Two sets of their data for four 0.5334-mm-diameter holes evenly spaced 8 mm apart (t = 40 mm) are illustrated. The first set, which is represented by the x symbol, is from an oxygen-free copper test section with an enhanced fin geometry. The o symbol represents data from a smooth-surfaced, aluminum test specimen. All of their data reside within the temperature-sensitive region. Consequently, errors due to position are negligible compared to those due to the temperature measurement. The uncertainty analysis is consistent with the data, since nearly all of the data points are below the graph for evenly spaced holes. In other words, the data agree with the analysis, since the observed error is less than the predicted limit.

Temperature Gradient Uncertainty

The standard deviation of the temperature gradient calculation can be estimated (s_g) by substituting Eq. (2) into the equation for the standard deviation of the slope of the fitted Ti versus xi line:

$$s_g = \sqrt{s_{T_i}^2 + \left(\frac{q''D}{6k}\right)^2} \sqrt{\frac{1}{\sum_{i=1}^{N}(x_i - \bar{x})^2}} \tag{6}$$

The estimated standard deviation of the temperature gradient calculation depends on the standard deviation of the individual temperature measurements (s_{Ti}), the diameter of the holes (D), the number (N) and arrangement of the thermocouples, and the absolute magnitude of the temperature gradient (q''/k).

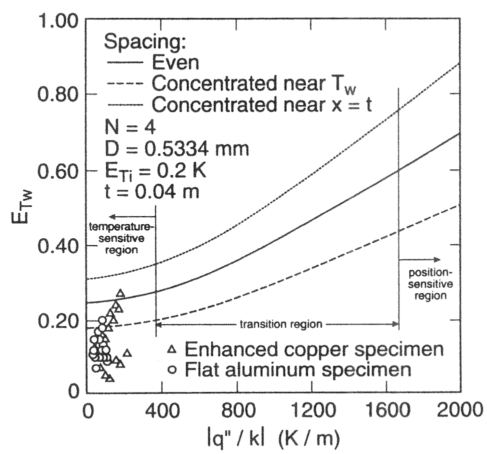

Figure 4. Effect of the magnitude of the temperature gradient on the accuracy of the wall temperature calculation.

Figure 5 illustrates the effect of the number and the arrangement of the thermocouples on the accuracy of the temperature gradient for a 99.7% confidence interval (E_g). The uncertainty of the temperature gradient calculation for a 99.7% confidence interval is equal to three temperature gradient standard deviations: $E_g = 3s_g$. Figure 5 shows the example case of a 0.04-m-thick specimen with a value of 0.2 for the dimensionless constant E_r and $E_{Ti} = 0.2$K. The arrangement of the aligned holes has little effect on the accuracy of the temperature gradient calculation. For example, the graphs for the two concentrated hole patterns are coincidental, which, in turn, nearly coincide with the graph for the evenly spaced holes. Although the hole pattern has little effect, the number of aligned holes can be increased to reduce the absolute uncertainty of the temperature gradient calculation (E_g). The uncertainty of the temperature gradient is reduced by approximately ± 5 K/m (63%) by quadrupling the number of holes from 5 to 20. Relatively large improvements in the accuracy of the temperature gradient are possible for N less than 6; however, the rate of improvement in the accuracy diminishes for values of N greater than this. For example, the E_g is reduced by approximately 44% by increasing the number of thermocouples from 3 to 6. Only a 20% reduction of E_g results for an increase in the number of holes from 6 to 9.

Figure 6 illustrates the effect of the thermocouple arrangement and the absolute magnitude of the temperature gradient on the percent accuracy of the temperature gradient ($\%E_g$) for a 99.7% confidence interval. The graph also includes the percent uncertainty of the temperature gradient measurements calculated from the experimental data of Kedzierski and Webb [2]. The data are from the same two test plates discussed above. As before, the x symbols represent data from the copper test section, while the o symbols represent data from the aluminum test section. All but one of the data points are within the uncertainty limits predicted as by Eq. (6). Consequently, the model appears to be consistent with the examined data. The agreement of the experiment with the theory also suggests that the effect of disturbed isotherms on the temperature measurement is not significant for 0.5334-mm-diameter holes.

Following is a summary of a procedure that can be used to design a test plate for accurate wall temperature and temperature gradient measurements. It is

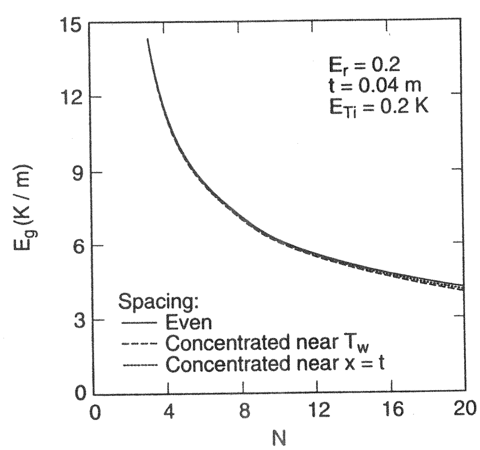

Figure 5. Effect of the number and arrangement of thermocouples on the accuracy of the temperature gradient calculation.

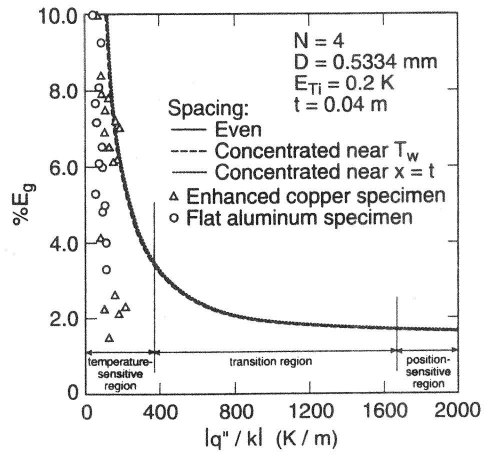

Figure 6. Effect of the magnitude of the temperature gradient and the arrangement of thermocouples on the percent accuracy of the temperature gradient calculation.

strongly suggested that the test plate be made of a material with a large thermal conductivity in order to ensure for a linear temperature profile. Also, it is recommended that one space the holes equal distances apart to avoid the uncertain effects of disturbed isotherms. Next, two design parameters should be determined: (1) the maximum heat flux that will be tested, and (2) the uncertainty of the individual temperature measurements. Use Eq. (4) with $E_r = 0.14$ to determine the required hole diameter that will ensure that the errors in q'' and T_w are within 1% of the minimum value. Choose the number and spacing of aligned holes and calculate the errors in the wall temperature and the temperature gradient calculations from Eqs. (5) and (6), respectively. If the errors are unacceptably large, then increase the number of holes and/or the accuracy of the individual temperature measurement (through calibration, etc.) and repeat the above design procedure. Once the number of holes, their size, and placement have been determined based on the above error analysis, the following procedure may be used to drill the holes.

HOLE DRILLING TECHNIQUE

This section is written for those who have limited resources and would like to drill holes inexpensively. Specifically, this article records a technique that has been developed for drilling small-diameter holes in copper for use as thermocouple wells. The procedure results in a negligible number of broken drills and is relatively inexpensive. This procedure advocates holes that are deeper than those traditionally recommended by conventional machining texts. The type of drill bit, the drill speed, the lubricant, and the general technique of drilling are presented in the following text.

Equipment

The basic requisite equipment for drilling micro holes in copper are the following: (1) a high-speed drilling apparatus, (2) heavy-duty twist drills, (3) a hole-positioning device, and (4) a center drill. The following section is a review of the specific requirements for each component.

The high-speed drilling apparatus must satisfy several specifications. It should be capable of angular velocities of approximately 30,000 rpm; however, holes can be drilled successfully at angular velocities as low as 3000 rpm. Excessive tool wear and consequently excessive tool breakage may result while drilling at the lower speeds. The drilling apparatus should also have the proper orientation for drilling holes. A high-speed drill press or a vertical milling machine can suit these needs. The drilling machine table must be sturdy and provide an area on which to firmly clamp the workpiece. Table rocking or vibration should be minimal. Since a vertical milling machine has a rigid setup and experiences negligible vibration at high speeds, it is preferred over a drill press. The motion of the drill chuck must be supplied by the most manual means possible in order to allow the feel of machining resistance. A sensitive hand-fed drill chuck is ideal for this. Micro holes can be accomplished without the special chuck, but greater care must be taken in order to avoid breaking a drill.

Most of the micro twist drills are jobbers. The drill has a straight shank portion, two cutting edges, and two flutes. The purpose of the flutes is to provide a passage for the lubricant and the cut metal from the bottom to the top of the hole. Heavy-duty high-speed steel (HSS) twist drills should be used. The flutes of the heavy-duty drills are not as deep as on regular HSS bits. Thus, additional strength is gained from the increase in shear area.

Special attention must be given to the drill point, since it is often not ground properly on micro bits. A bad drill point will cause the hole to be mislocated or to be bellmouthed, which will increase the chance of breakage. Figure 7 is a schematic of two of the most common drill points, standard and split point. A split-point drill is recommended since a heavy-duty drill with a standard point would have extremely thick webs, which may cause misalignment of the hole and reduced cutting efficiency. The web of a split point is beveled to reduce the width of the point. Using an optical comparator or a microscope, examine each tip before use and compare it to the split point shown in Figure 7. Discard those drills that have the following: (1) tips not centered on the web, (2) webs thicker than that of a

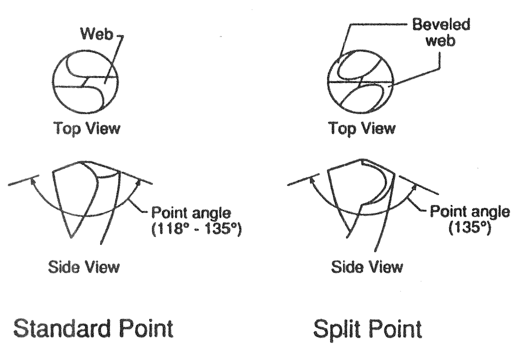

Figure 7. Schematic of properly ground drill point.

split point, and (3) point angles not within 118° to 135°. It is advantageous to purchase a good grade or brand of drill in order to reduce the expense associated with discarded and broken bits.

A numerical series #75 twist drill should be used to provide a hole for a 0.508-mm-diameter sheathed thermocouple. The 0.5334-mm diameter of the #75 bit provides for a snug interface with the thermocouple. Oil should fill the space between the hole wall and the probe to ensure thermal contact between them.

Some means must be provided to position the drill over the workpiece. Vertical milling machines that are equipped with computer numeric control (CNC) or digital readout systems will serve this purpose. An inexpensive method, if a CNC or digital readout system is not available, is to make a hole template out of a 1.6-mm-thick metal plate. The template should have the desired hole pattern and a reference point from which to align it with the heat transfer surface.

A center drill should be used to start the hole. The starter hole helps in centering the twist drill so that the hole is drilled straight. A center drill has identical ends, i.e., two cutting points. The diameter of the cutting point should be slightly smaller than the diameter of the twist drills. A "000" center drill with a 0.43-mm-diameter cutting point was used to start the hole for the #75 drill. The starting hole should be drilled to a depth that produces a chamber with a maximum diameter of 0.635 mm to 0.762 mm.

Drilling Concerns

The primary objective is to machine holes in a relatively short amount of time without breaking the drill. If a drill bit breaks, it will remain lodged in the hole. The broken tool must be removed. Otherwise, the bit will distort the isotherms and prevent the holes from being evenly spaced. It is unlikely that the bit can be drilled out. Instead, EDM should be used to remove it and to finish the hole. Drill breakage can be minimized if close attention is paid to the drilling speed, the feed rate, and the lubricant.

The cutting edge of the drill must have sufficient speed in order to cut the metal. On the other hand, if the cutting edge travels too rapidly, it may produce a powder that becomes packed into the bottom of the hole, forming a smooth-surface layer that resists machining. The *Machining Data Handbook* [10] recommends cutting speed (S) ranges for several metals. Cutting speeds from 0.25 to 1.15 m/s are specified for various copper alloys. The authors found, by trial and error, that an angular velocity (V) of 28,000 rpm ($S = 0.78$ m/s) produced the optimum cutting speed for the #75 drill bit in copper. By using the recommended cutting speed, the angular velocity can be estimated, for other drill diameters (D), as follows:

$$V = \frac{60S}{\pi D} \tag{7}$$

The feed rate is probably the most important and most difficult aspect of the micro drilling process. For drilling deep holes, the *Machining Data Handbook* [10] recommends drilling to a depth equivalent to the bit diameter before lifting the bit out of the material. Another source, *Materials and Processes in Manufacturing* [11], recommends 0.03–0.05 mm per revolution (mmpr) for holes less than 3 mm in diameter. This book describes the drill feed for deep holes as a "pecking" action, which best describes the method advocated by this article. The authors found that by keeping a constant pressure from peck to peck, the feed rate was determined by the pecking action itself.

The "pecking cycle" is best realized with the sensitive drill chuck. Since the drill is hand fed, the machinist can feel the slightest resistance. The machinist should practice the drilling cycle on a scrap piece of block material in order to learn by experience the amount of resistance that can be applied without breaking the bit. In general, the machinist should apply less pressure than that which would result in a noticeable reduction in the speed of the drill. The depth of each peck should be approximately equal to the diameter of the drill, e.g., approximately 0.5 mm for the #75 bit. The drill should touch the bottom of the hole for approximately 1 s. As the hole becomes deeper, the time of contact or machining becomes shorter. Consequently, less material will come out of the hole. If necessary, the *Machining Data Handbook* [10] provides a table for reduced speed and feed rates for increased hole depths. However, the tabulated values should be used only as a starting point from which to determine the optimum speeds and feeds from experiment.

The lubricant is used to cool the drill bit and to aid in the removal of the cut metal from the hole. It also diminishes friction at the cutting edges, which prevents tool wear and breakage. The lubricant should be a mineral oil base; the oil should not evaporate readily. Otherwise, it will not be fluid for a sufficient time to aid in the removal of the metal cuttings. Add wax to the lubricant in order to increase its adhesion to the metal.

Oil-hole or pressurized-coolant drills would be ideal for the deep hole application. Unfortunately, micro oil-hole drills are not made commercially. Oil-hole drills permit hole depths up to 30 diameters. However, the authors were able to drill holes to a depth of 19 mm (36 diameters) with the heavy-duty twist drill.

Drill bit wandering or curving away from the drill axis is due to the flexibility of the drill. Wandering can be avoided by using a center drill as described previously. An additional precaution is to start with only 6 mm (or 10 diameters) of the twist drill exposed past the chuck. Drill the hole to the depth of the exposed portion of the bit. Let out an additional 6 mm of bit and drill until the chuck bottoms out again. Repeat the process until the desired hole depth has been reached.

Recommended Drilling Procedure

The following procedure for drilling micro holes in copper was developed for use with #75 drill bits. However, the steps are flexible enough to be applied to other size drills.

1. Observe standard safety procedures. Wear safety glasses. Avoid loose-fitting clothing.
2. Practice drilling on a scrap piece of metal. A few bits will probably be broken during this session. Don't be discouraged.

3. Secure the metal block to the table of the drill press or vertical milling machine with a clamp. If a hole template is used, clamp it to the working surface.
4. Use a center drill to start the hole.
5. Expose only 6 mm of the drill bit at a time to avoid drill bit wandering.
6. Position the drill to the desired location of the hole using the template, CNC, or a digital readout.
7. Lubricate the hole and bit.
8. Operate the drill at an angular velocity calculated from Eq. (9) and move it to meet the surface.
   a. Examine the drill for wandering. If the hole is not drilling straight, reduce the length of the bit exposed past the chuck.
   b. Apply a small amount of even pressure. Let the drill do the work. This ensures a straight hole and avoids drill breakage.
9. Once the hole has been started, the drilling motion should emulate a "pecking" action given as follows:
   a. Lower the drill so that it touches the bottom of the hole with slight pressure for approximately 1 s or until a slight resistance is felt. The amount of pressure to apply will become evident as the machinist gains experience.
   b. Bring the drill and, thus, the metal chips entirely out of the hole.
   c. Wipe the chips and the lubricant from the working surface with an acid brush. The acid brush is used because the metal chips adhere well to it.
   d. Wipe the chips from the acid brush.
   e. Apply fresh lubricant to the bit with the acid brush.
   f. Repeat steps 8*a*–8*d* until more of the drill needs to be exposed or the depth is achieved. Remember to expose only 6 mm at a time to ensure a true hole.
      (1) If necessary, use the hole to help keep the drill aligned with the block when rechucking the bit.
      (2) When close to the desired depth, chuck the bit and measure so that it projects passed the chuck to the desired depth. Drill until the chuck meets the surface for a finished hole at the correct depth.
10. Drill only two to three holes per drill bit. An overworked bit becomes dull and is more likely to break.

CONCLUSIONS

An analysis has been presented that reveals the important parameters for reducing the errors associated with the uncertainty in the location, the temperature measurement, and the arrangement of the thermocouples. In general, the error analysis agrees with statistical data obtained from condensation heat transfer measurements from an aluminum and a copper test specimen. A test plate designed to reduce measurement errors should be made from a material of high thermal conductivity with widely spaced, small-diameter holes and accurately calibrated thermocouples. The errors in the calculation of the heat flux and the surface temperature can be further reduced with an increase in the number of thermocouples. Special hole arrangements can be used to increase the accuracy of the calculation of the surface temperature; however, the hole arrangement has a negligible effect on the accuracy of the heat flux calculation. A design procedure has been presented to determine the maximum hole diameter that still ensures that the errors due to the uncertainties in the position of the thermocouple are negligible.

This article also presents a specially adapted procedure for drilling deep, micro holes in copper. The required equipment is (1) a high-speed drilling apparatus, (2) heavy-duty twist drills, (3) a hole positioning device, and (4) a center drill. A vertical milling machine is recommended, but a high-speed drill press can also be used. Heavy-duty twist drills with properly ground points must be used. A hole template, CNC, or digital readout may be used to position the holes. A center drill is used to start the hole and is also used to avoid wandering of the drill bit while drilling.

Drill breakage can be minimized if close attention is paid to the following machining parameters: drilling speed, feed rates, and lubricants. The drill speed must be high enough to cut the metal, but it must be low enough to avoid creating a metal powder that hampers the drilling process. The feed rate is described as a "pecking" action, which drills to a depth of the diameter of the bit with each peck. The drill bit should be cleaned between drill cycles with an acid brush and a mineral oil-wax mixture that attracts the metal shavings.

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