Diamond Dies for the High-Speed Drawing of Copper Wire*

By H. N. PADOWICZ

ESSENTIAL to the drawing of copper wire at any speed are the dies to effect the desired reduction steps. It can be readily surmised that this item is one of major importance at drawing speeds of 10,000 and 12,000 feet per minute which are being used in the copper wire drawing plants at the Kearny Works and the Baltimore Works of the Western Electric Company.[1] In these machines diamond dies are used to draft 12 and 14 A.W.G. supply wire to the final sizes of 19, 22, 24 and 26 A.W.G., respectively. As pointed out in the paper[1] describing these machines in the above noted plants, the maximum possible drawing speed is limited by the stresses set up in the take-up reel rims. Drawing dies in themselves should not place any limitations on the wire drawing speeds if the factors of heat generated and the rapid movement of lineal wire surfaces are logically considered and provided for.

In 1924 the manufacture of copper wire at a drawing speed of 2500 feet per minute in a new type of wire drawing machinery, developed and designed by the Western Electric Company, was started in its Chicago plant.[2] At that time copper wire was being generally produced at speeds ranging from 800 to 1200 feet per minute. A study of the manufacture of diamond dies for use in these machines developed that dies suitable for this work required a differently shaped "approach," a better polish and a shorter "land" than those that were available for low-speed operation. These same factors are still the important items which must be considered for today's drawing speed of 10,000 and 12,000 feet per minute.

The technique of making diamond dies for the drawing machines which operate up to about 5,000 feet per minute is now well established. The specifications covering the dies for this purpose are known and available to the trade which is well qualified to produce them. However, the opportunity and necessity for diamond dies to draw copper wire at the noted high speeds did not exist prior to the recent development of these high-speed machines and for this reason the industry was not familiar with the necessary die requirements.

The Kearny Wire Mill was set up to purchase finished mounted dies from outside suppliers and to recut them when oversize. These dies are usually acquired at the smaller final sizes as governed by production schedule requirements and enlarged to the larger sizes for both finisher and line die use.

* Published in *Wire and Wire Products*, October, 1941.

A large part of the success attained was due to specifications defining the die requirements and the setting up of adequate inspection means to check the new and recut dies for these requirements. Prior experience of this company and the cooperation of our suppliers greatly aided this policy.

The following details of diamond wire drawing dies have been found to be essential to the desired performance of these tools in our drawing operations:

Shape and Quality of the Diamond Stone
Stone Size
Mounting
Contour of the Die Hole
Polish and Finish
Pounds Pull to Draw the Wire through the Die

Shape and Quality of Diamond Stones

Round, clear stones of sound structure are selected, and these should be free from cracks, pits, carbon spots, porosity or any flaws and imperfections which would affect the present or recut drawing surfaces of the die. *Round* is the trade term for stones of polyhedral sides, approximating a spherical form as distinguished from flats and irregular, unsymmetrical shapes.

Usually these stones are octahedral in habit with smooth rounded corners. The coloration and clarity of the mounted stone should permit inspection of all drawing surfaces, relief angle, approach angle and bell. A close-grained stone as determined by the crystal growth lines seems best.

Stone Size

The size of stone for specified hole sizes, consistent with the quality of stone previously noted, has been well standardized for the copper wire industry by the American wire die manufacturers. Good die performance has been obtained from these sizes. The average stone size of these manufacturers has been specified for our requirements.

Mounting

The mounting encasing the stone is a vital factor in the life of diamond wire drawing dies. Diamonds when used for drawing dies ultimately fail by breakage (i.e. cracks, spalling, chipping out) and not by erosion of the wearing surfaces. Diamonds due to their formation and crystalline structure and to the physical properties resulting therefrom, are particularly prone to breakage when subjected to fatigue, impact and disrupting tensile stresses such as those commonly met in wire drawing operations. To compensate for this weakness it is necessary to effectively encase the stone in a mounting which adequately supports it on all sides. The methods of mountings are many and varied. Mountings which are made by hot pressing, forging or upsetting to obtain definite bonding of the component parts were found to be superior to those made by brazing, puddling, or casting. High-strength metals processed with the proper technique to effect good metal flow and alloying bonding are preferable. The interface of the stone and metal should be free from porosity and crevices. Figure 2 depicts a defective mounting due to poor metal flow which caused the early breakage of the stone.

Contour of the Die Hole

The contour of the die hole is shown in Fig. 1. It is the familiar radial or parabolic type which is commonly used in the copper wire industry with

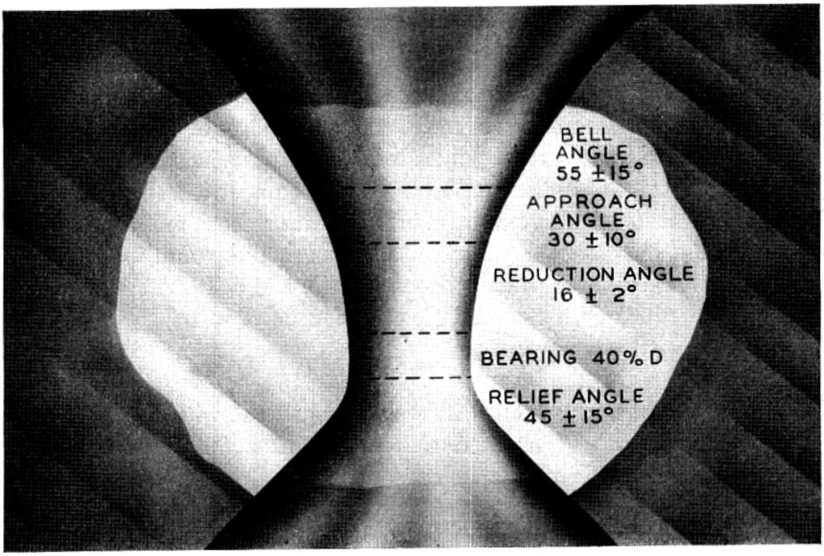


Fig. 1—Contour of the die hole

good results. The straight angles associated with cemented carbide dies do not exist in the present day commercial diamond dies. The noted angles are arcs and the values cited refer to the average chords subtending these arcs. In agreement with the findings of comparatively recent English investigations[3] of the theoretical factors affecting wire die performance, it was found that small changes of angle do not appreciably influence the die pull. Whatever differences do exist are blanketed out by changes in the die frictional forces. The permissible variations in angle are consistent with the average found in today's best commercial dies. In recutting dies obtained from different sources the variations narrow after one or two recuts. This is to be expected when standardized recutting practises are followed.

Bell Angle

The bell angle should permit ready ingress of the compound solution to wash out those materials (dust, slivers, sludge, dirt, etc.) which tend to accumulate here and have an abrasive action when pulled through the die

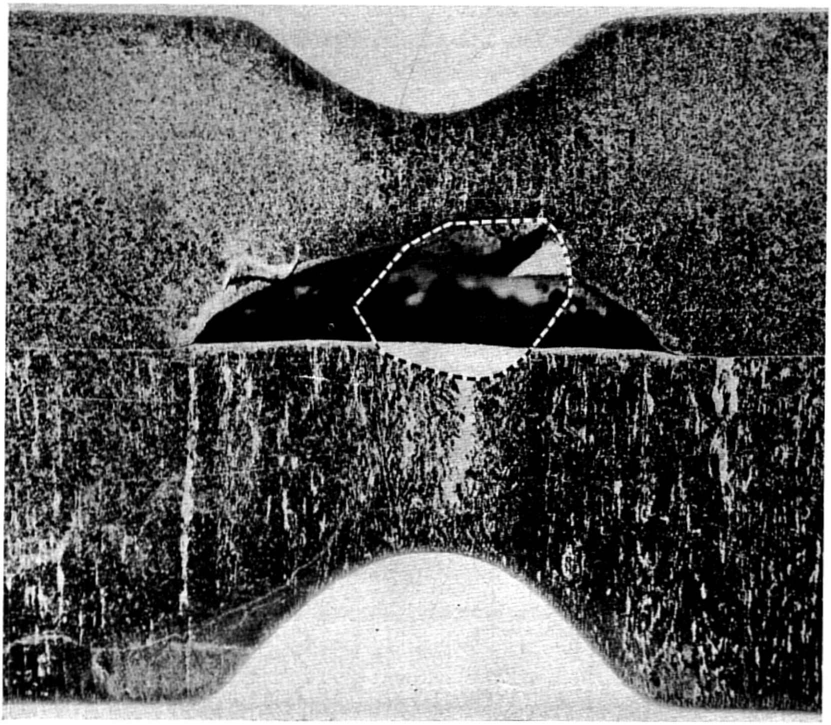


Fig. 2—Defective diamond die mounting due to poor metal flow

by the wire. The bell angle is highly polished to minimize the packing of the noted materials. This polish can be more easily achieved in a smooth tapering angle than in one of a wide flare.

Approach Angle

At high drawing speeds, appreciable wire whip and vibration are present. Also, the higher centrifugal forces tend to "throw out" the wire in relation to the normal axis of the die. An approach angle not too wide in relation to the reduction angle is necessary to guide the wire concentric to the drawing cone.

Reduction Angle

In this angle, the most important sector of the die, the reduction of diameter, except for the sizing accomplished in the bearing, is carried out. Following the practice of the trade a 16° angle is used. The depth of this area is designed to have the entering wire hit well within it to prevent excessive chipping and undercutting in the pressure ring and to maintain the desired die pull values. The line of contact of the entering wire and the reduction area is located at 65–70% of the vertical height of the reduction angle.

In general, the ratios of the vertical heights of the reduction, approach and bell angles are as follows: 1:0.7:1.5 for dies of 20–26 A.W.G. inclusive and 1:0.5:1 for the larger sizes. The dimensions of the approach and bell angles are of course dependent on the stone size and the number of previous recuts. The heights of the two latter angles may vary appreciably from the above noted values provided that adequate lubrication and "washing out" of the die can take place.

Bearing

A bearing length of about 40% diameter is formed. It is checked by the die pull requirements. The bearing is purposely drilled to obtain a slight front taper of about 2°. The slight taper aids the metal flow and reduces "sucking".

Relief Angle

Here again, the wire vibration necessitates a smooth angle which will not tear the wire leaving the die. Recutting for good reproduction of contour and die pull also requires a smooth angle. Proper care should be taken to prevent a cup shaped depression which is commonly formed by jamming a diamond chip in the back of the die as a fast intermediate step to final sizing.

Polish and Finish

The degree of polish of the die drawing surfaces is a most important factor in determining satisfactory die performance. In wire drawing there is encountered a vicious repetitive cycle consisting of (1) the wire abrades due to the condition of the wire and die surfaces, (2) the resultant abraded metal particles pack in the die throat and gall the incoming wire, and (3) the heat and the conditions created by this action again adversely affect the wire and the die surfaces to repeat the cycle. There have been cases noticed where the fine copper particles have been compacted by the heat and pressure to form a solid conical mass which has welded to the wire. Deep grooves in the reduction angle and bearing invariably follow back to the pressure ring or irregularities in the die surfaces in which the metal particles, dirt, etc. have lodged.

Characteristic of copper and other non-ferrous metals is its ready flow under pressure such as is present in the die reduction angle. This condition causes die packing, metal galling and the resultant wire scoring to take place at surprisingly slight irregularities in the die drawing surfaces. This is particularly true at high drawing speeds due to the rapid lineal movement of the wire surfaces. Again, this emphasizes the necessity for a high polish. The harder ferrous metals tend to bridge across these small irregularities rather than to flow into them.

Highly polished surfaces free from scores, traces of ripping rings and scratches are desired. All the die surfaces with the exception of the relief

TABLE I

Diamond Die Diameter	Max. Pounds Pull	Diamond Die Diameter	Max. Pounds Pull
13 A.W.G	113	20 A.W.G.	25
14 "	92	21 "	21
15 "	75	22 "	17
16 "	60	23 "	13.5
17 "	49	24 "	11
18 "	39.5	25 "	9
19 "	32	26 "	7

angle and top flare of the bell should be so finished. The polished surfaces should be a smooth curve as undulating surfaces are undesirable.

Dies after full use to oversize will retain their original high polish if no breaks in the stone, i.e. chips, cracks, etc. have occurred. This polish will also be present in the wear eroded areas.

POUNDS PULL TO DRAW THE WIRE THROUGH THE DIE

Die pull has long been known to the trade as a factor which greatly influences wire drawing operations. However, it has not been customary to recognize its relation to the drawing die itself and it has not been applied as an everyday simple means of checking a die's possible performance. The Western Electric Company has considered for a long time this die characteristic in its wire drawing developments[4] and practical values for use in the present high-speed drawing machines have been established. Listed in Table 1 are the values used for these dies. It should be added that, while die pulls are important, these are not critical and a deviation of +10% can be used but this would result in greater power consumption and more frequent wire breaks. The noted figures are 45–50% of the wire breaking strength based on A.W.G. reduction steps. Die pull is a cumulative check of the following die characteristics: contour as correlated to the reduction angle and bearing length, and the polish of the drawing surfaces. In conjunction with the die diameter, it affords a means of grouping the dies in matched balanced sets and obviates actual try out of these dies in the machines.

Inspection Methods

Suitable inspection methods and equipment to check the die requirements contribute much to good die performance. Microscopes have been used with good results by some manufacturers of fine wires and by several of the more progressive die manufacturers for some time for this purpose. The Western Electric Company has adopted this practice. The binocular wide field microscope has proved to be an indispensable tool for inspection. It is used to the complete exclusion of loupes. The stereoscopic effect, the wide field and the long focal distance features of this instrument make satisfactory examination possible. We have found a magnification of 30× to be most practical for the previously noted die sizes. Good agreement to observations by different persons can be had by the use of this apparatus. This is a rare occurrence in the case of loupes. It is surprising that this inexpensive tool which removes much of the guessing and so-called art in diamond die manufacture has not been universally utilized by wire drawers and die manufacturers.

Frequent examination of finished dies and dies in the various stages of recutting is expediently accomplished by microscopic observation. Routine die contour checks are visually made in this manner. Periodic checks of die angles and die contour are accurately made with a contour projector. Shadowgraphs of 100× magnification are made of die impressions formed of a soft metal.

When polished to the proper degree, it is possible to examine a mounted die under a microscope with a suitable light source and discern the internal flaws in the stone. The examination of stones removed intact from the mounting will also check this point. Mountings of metals having a low reflectivity will require a light source from above to illuminate the stone.

The die pull is checked on a commercial instrument shown in Fig. 3. Auxiliary equipment and gauges have been added to it to make it more versatile for this use. The device consists of a piston which fits snugly into a hydraulic chamber filled with a suitable liquid. The piston is recessed at the outer end to hold the die. The die pull causes the movement of the piston which builds up the registered pressure. The wire is reduced one A.W.G. step and the pressure against the die holder is noted as indicated on

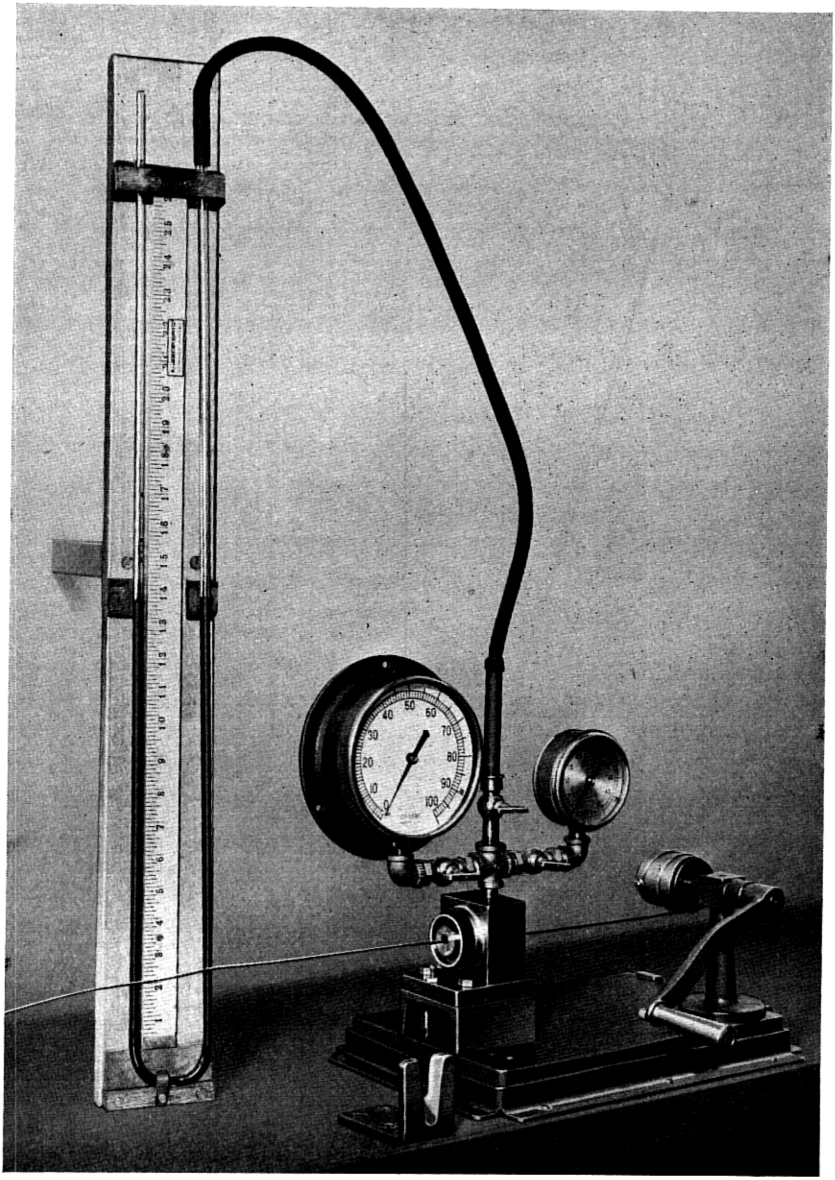
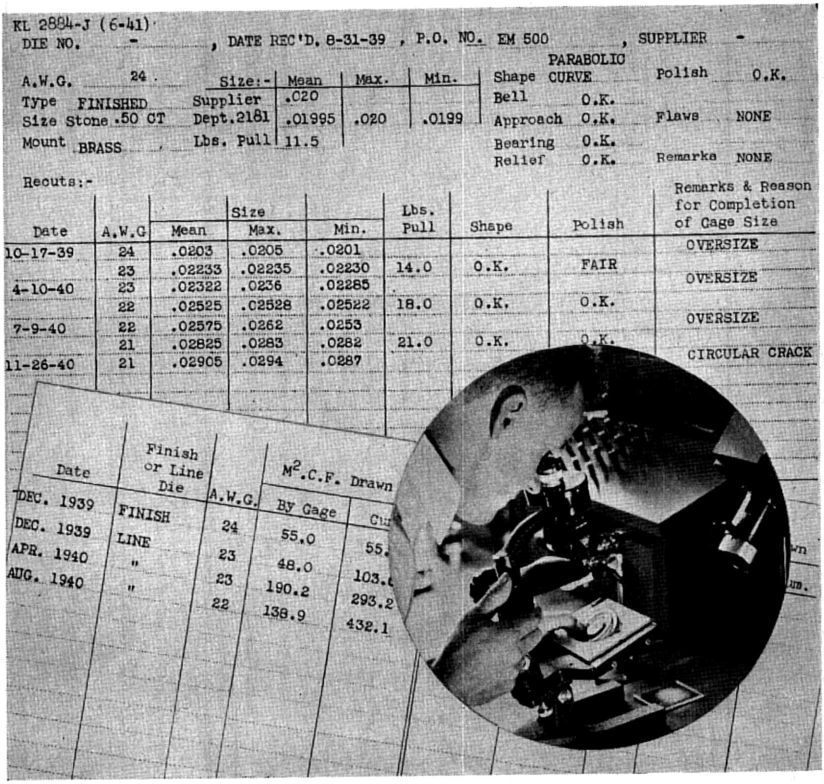


Fig. 3—Die pull indicator

the adjoining gauge. Small die sizes having die pulls below five pounds are checked by means of a manometer filled with an appropriate liquid. When measuring die pulls of low magnitude, the device should be calibrated for the frictional drag of its moving parts.

Die Records

Die control is greatly enhanced by comprehensive records. All dies are logged on individual record cards. A facsimile of each side of this card is shown in Fig. 4. As noted, the individual die characteristics as received, at oversize, and after recutting to final disposition are recorded. These


KL 2884-J (6-41)
DIE NO. -, DATE REC'D. 8-31-39, P.O. NO. EM 500, SUPPLIER -

A.W.G. 24
Type FINISHED
Size Stone .50 CT
Mount BRASS

Size:-	Mean	Max.	Min.
Supplier	.020		
Dept.2181	.01995	.020	.0199
Lbs. Pull	11.5		

Shape PARABOLIC CURVE — Polish O.K.
Bell O.K.
Approach O.K. — Flaws NONE
Bearing O.K.
Relief O.K. — Remarks NONE

Recuts:-

Date	A.W.G	Size Mean	Size Max.	Size Min.	Lbs. Pull	Shape	Polish	Remarks & Reason for Completion of Gage Size
10-17-39	24	.0203	.0205	.0201				OVERSIZE
	23	.02233	.02235	.02230	14.0	O.K.	FAIR	
4-10-40	23	.02322	.0236	.02285				OVERSIZE
	22	.02525	.02528	.02522	18.0	O.K.	O.K.	
7-9-40	22	.02575	.0262	.0253				OVERSIZE
	21	.02825	.0283	.0282	21.0	O.K.	O.K.	
11-26-40	21	.02905	.0294	.0287				CIRCULAR CRACK

Date	Finish or Line Die	A.W.G.	M^2.C.F. Drawn By Gage	Cu...
DEC. 1939	FINISH	24	55.0	55.
DEC. 1939	LINE	23	48.0	103.
APR. 1940	"	23	190.2	293.2
AUG. 1940	"	22	138.9	432.1

Fig. 4—Facsimile of a die record card

cards are periodically correlated to the daily machine performance sheets by mechanical tabulation to obtain the die life.

Shop Die Control

All drawing dies are grouped in sets for use and matched for balance in relation to their diameters. This is necessary because of the minimum slip characteristics of the drawing machines. It is also a convenient means to reduce machine down time. The sets are used in the drawing machines as units. Replacements and rematchings are made in the Die Shop. Definite oversize diameter limits consistent with best enlargement practice and overall operating efficiency have been set for each finisher and line die size. The die sets are removed from the machine when any one die, with the exception of the finisher, has reached the specified limit. Usually two finishers are used for each set of 26 A.W.G. and one plus for the other final gauge sets before returning these units to the Die Shop. This procedure has greatly enhanced the economics of die costs, operating efficiency and wire quality. It has also made possible the issuance of dies by the Die Shop for shop use without the necessity for preliminary "tryout" in the drawing machines.

Recutting Practice

Diamond die recutting is a series of lapping operations in which the abrasive is diamond dust for obvious reasons and the lap or carrier is a suitable pin or wire, usually steel, depending upon the specific operation. The theory and practice of lapping tool gauges to a fine finish is applicable here. The diamond dust imbeds in the lap, is held there temporarily stationary and cuts the die stone when it is forced in contact with it. As its position is fixed relative to the lap, but moving with respect to the stone, it cuts the die surface. However, due to the great hardness of diamond, appreciable wear of the lap takes place and its shape is rapidly changed. In ripping where the shaping of the die contour is done, the pin must be frequently reground. It is necessary to have a hard material for the lap to keep the diamond dust working in contact with the die surface and to retain its shape for an appreciable time. Also, some diamond dust would imbed deeply in a soft material and be removed in the grind.

Successful recutting and reproduction of die characteristics require definite procedures and controls. Specific hole size enlargement, surface requirements, frequency of lapping pin grinds, diamond dust additions, etc. are essential for each operation to achieve the desired results.

Standard commercial machines are used for the various enlarging and refinishing operations. In general, recommended trade practices are followed.*

Ripping (the roughing operation which removes the pressure rings, chips, etc. and reshapes the die contour) is most important as it determines the die contour and the subsequent degree of polish. We have found the RPM of the drilling pin spindles to be a determining factor. Spindle RPM's from 4,000 to 12,000 have been tried, and 5,000 RPM has been found to be most satisfactory. Other important elements are the diamond dust size, frequency of pin grinds, speed and kick of the reciprocating vertical motion. A definite sequence of these factors is necessary to achieve the desired results. A gradual breakdown of the diamond dust effecting a cutting and lapping action as controlled by the centrifugal forces dispersing it in the liquid medium takes place. The steel lapping pins are accurately ground to a definite straight included angle and circular arc on a special grinder. The ripped die surface should be a smooth, dull matte surface free of deep rings and scores.

In polishing, the die contour has already been established and it is expedient to have the lap of a material which will rapidly shape itself to the contour to be polished to obtain maximum contact. Here the loading of the lap will hold the diamond dust in contact with the work. A viscous medium for the dust will also help. On the wire polishing machines, the springback of the wire on flexing is important. It was found that a wire resiliency tester will aid to evaluate the desired wire properties. Diamond dust of a uniform and fine grain size is vital to the polishing operation. High RPM in the case of revolving die mounts is beneficial provided it does not "throw out" the diamond dust from the working area.

Sizing of the bearing requires a spindle RPM about 100% higher than that used in ripping. Other factors in this operation are the diamond dust, frequency of its addition and the frequency of the pin grinds.

All die recutting machines should be periodically checked and maintained to minimize vibration.

Diamond Dust

Another important factor in the recutting operations is the diamond dust abrasive. This is especially true in the finishing operations of polishing and sizing where no appreciable breakdown of the original dust takes place. Uniformity of particle size range and grain size determine the efficacy of the abrasive. Diamond dust graded by air flotation is now being used with good results. It was found that this material was more satisfactory for our use than that obtained by sedimentation in liquid media. Recent investigations in the separation of microscopic size dry powdered material have been actively carried out in the ceramics and powdered metal industries. The Journal of the American Ceramic Society and the Bureau of Mines publications contain noteworthy papers describing practices which could be applicable to diamond dust grading. Stokes[5] law of fall for microscopic size particles will also hold true for the separation of diamond dust by means of air.

Die Life

In theory and practice, die life resolves itself into a problem of wear. The wear is due to the movement of the wire surface over the drawing die area in contact with the wire. In turn the wear is proportional to the forces acting on these surfaces, their area, the condition of these surfaces and the coefficient of friction. This is dependent on the nature of the wire, the die materials and the lubrication of the contacting surfaces which in turn is affected by their condition. Considered on this general basis, the die life is proportional to the wire lineal footage. A good criterion for determining the overall diamond die performance is the total useful life in million conductor feet. This in turn will be proportional to the number of recuts obtainable before breakage renders the die non-usable.

Although diamond die life is theoretically a function of wear, actually it is limited by the failure of the die stone by breakage and "chipping out." Due to the peculiar physical properties of diamonds some breakage will always occur. This condition is also affected by fatigue caused by vibration, impact, thermal stresses and other factors. An important element influencing die breakage which is often overlooked is the detrimental effect produced by improper maintenance of the drawing machine parts. An appreciable reduction in die breakage was obtained by proper periodic maintenance checks.

TABLE II

B & S Ga.	Kearny Wire Mill 1/39–8/40					
	Finishers		Line Dies		Average*	
	M Lbs.	M.²C.F.	M Lbs.	M.²C.F.	M Lbs.	M.²C.F.
26	35	45	—	—	35	45
25	—	—	90	93	90	93
24	92	75	105	86	97	79
23	—	—	162	108	162	108
22	136	70	159	82	148	76
21	—	—	226	92	226	92
20	—	—	250	81	250	81
19	250	64	284	73	277	71
18	—	—	368	75	368	75
17	—	—	595	96	595	96
16	—	—	740	95	740	95
15	—	—	1040	106	1040	106
Average M.²C.F. per die gauge step						85

NOTE: Some of the results listed above appear to be inconsistent with the expected trends. This is attributed to the many variables which exist in normal Wire Mill Operations.

* Based on Kearny's distribution of gauges.

Kearny's Wire Mill diamond die life data are listed in million conductor feet per die per gauge step in Table II. The finisher and line die life is tabulated separately to account for the allowable oversize diameter limits for each type. No data are available at the present time to permit listing of the total useful life in million conductor feet.

Strains in Diamond Stones

Rough diamond stones as well as those removed after use in drawing dies have been examined in polarized light to determine the presence of internal strains. In general, the clear flawless stones of alluvial origin were free of strains. Mined stones of South African origin which are commonly found in dies of French manufacture did show in several cases very definite strains. These latter stones were of poor quality. Due to the high index of refraction of the diamond which is much higher than available high refractive liquids, and to local surface strains which distort the interference figures, it was impractical to establish a satisfactory procedure to investigate this subject.

Crystallographic Studies

In several cases exceptional die performance was noted, three to four times the average, which could not be accounted for by our regular inspection methods. Also, several dies which chipped initially in use, consistently chipped at subsequent recut sizes after enlargement had completely removed the visible defect. Again and most important is that the majority of our dies are rendered non-usable by the breakage of the die stone, which occurs in a characteristically peculiar manner. These discrepancies are attributed to the crystallographic structure of diamonds. It is well known that the reticular density (atom spacing), hardness and cleavage are greater along certain crystallographic planes.

Investigations as to whether or not the relation of the planes of cleavage to the direction in which the hole is drilled has any practical bearing on die life were made by the Western Electric Company in 1929[4]. The x-ray was used to determine the orientation of the crystal planes. The results of a limited test at that date, in which nineteen dies were drilled at right angles and nine parallel to the plane of cleavage, showed no superiority of these positions. The diamond stones used for dies then were of different origin and quality than those now commonly empoyed for this purpose. Further studies, with particular reference to the relation of crystal structure to die breakage, are now under way for reasons noted previously, and some of our results to date are cited here having a bearing on die performance.

It is well known that hardness in a diamond varies with the crystal planes. However, since the contour of the die hole consists of cylindrical and conical surfaces, it is questionable if this plane property could be effectively utilized in drawing dies.

An x-ray method[6] on a shop production basis is now being used to orient quartz plates preparatory to their cutting along certain crystallographic planes incident to their manufacture into radio and carrier frequency control filters. A similar technique was applied to determine the location of the axis of the die drawing hole with relation to the diamond structure. The orientation of the drilled hole was determined by means of a back reflection Laue photograph.

Diamond stones which meet our drawing die requirements are mostly octahedral in shape, a common crystal form of this material. These are usually alluvial in character and predominantly of Brazilian origin with the exception of a few Southwest African stones.

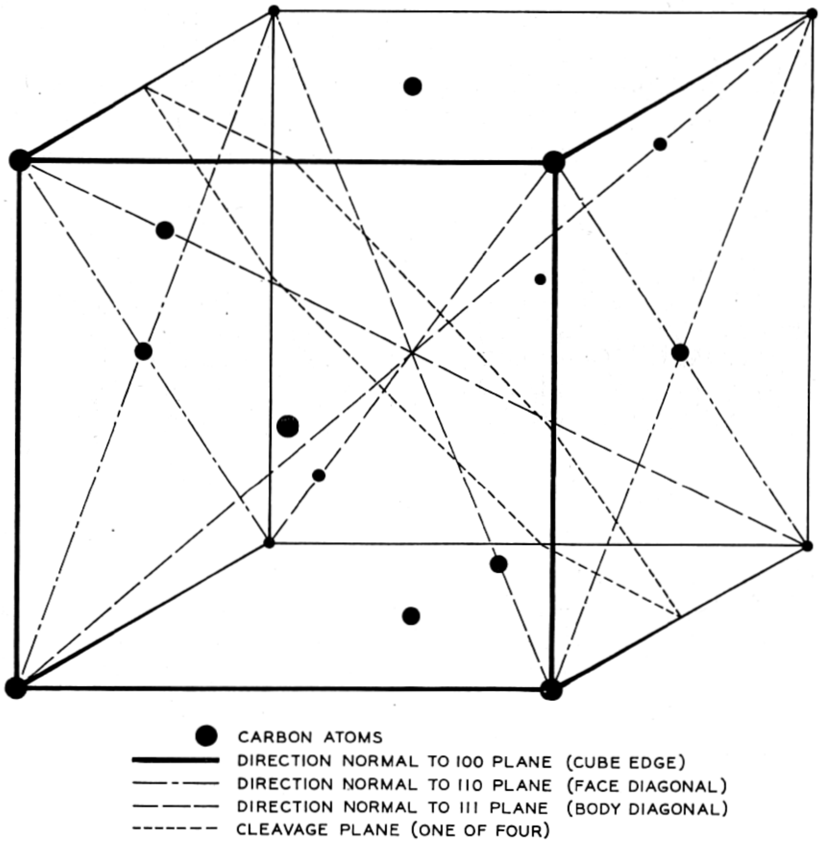
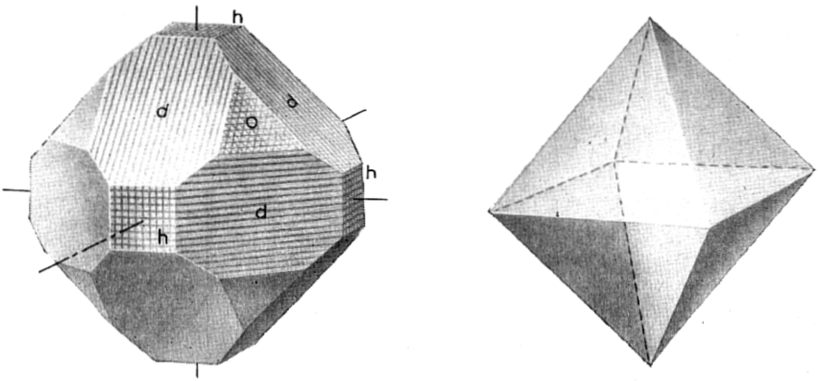


Fig. 5—Diamond structure and the directions of drawing hole axis to the crystallographic planes

Our examinations of numerous die stones have shown that the positioning of these is random with regard to a predetermined drilling axis. About 75% of those studied were drilled normal to the 111 orientation. The axis of the drawing hole in these cases was in the direction of a body diagonal of the cube representing the crystal structure of the diamond. The 111 planes, the cleavage planes for the diamond, are those which appear most frequently as the natural faces of the most common form of the diamond crystal, the octahedron. The disposition of the stone in the above manner would be logically expected to take place in the mounting methods generally used by the American die manufacturers since the stone would probably rest on a flat side, an octahedral face. This placement for very obvious reasons also facilitates cutting true the starting cone for the drilling operations.

A few stones had been drilled normal to the 110 and 100 planes or at an angle to the 111 plane. Holes normal to the 110 plane, which is the face of the rhombic dodecahedron, another diamond crystal form, are along a face diagonal of the cube. Holes normal to the 100 plane, which is the cube face,



A B

Fig. 6[7]

A—Diamond crystal showing grain and faces (crystallographic planes)
h. Cube face.......................................100 plane
d. Rhombic dodecahedron.........................110 plane
o. Octahedron ....111 plane

B—Diamond octahedron

are along a cube edge. Very few of these were found. This is as expected since natural crystals with faces parallel to the 100 plane are rare. This face is usually produced by sawing or "bruting."

As previously noted, diamond die life is restricted by the breakage and "chipping out" of the stone. The manufacture of the dies with due consideration of the peculiar crystallographic structure of the diamond to minimize this condition should greatly enhance its performance. Findings to date substantiate this conclusion. Seventy per cent of the dies which were drilled normal or at a small angle to the 111 plane failed due to cracks parallel to this plane and normal to the drawing axis. The crack usually occurred at the pressure ring and its plane coincided with the cleavage plane, the weakest one in the diamond crystal. The stone in many cases on removal from the metal mounting separated into two sections. The majority of the dies failed in this manner.

Examination of worn oversize dies invariably shows that the erosion and the effect of the forces incident to wire drawing are concentrated at the pressure ring where the entering wire contacts the reduction area. Here, the abrasive action of the wire and die contacting surfaces, and the disrupting stresses are most evident. An analysis of the forces present in a wire drawing die indicates that secondary stresses normal to the drawing axis are set up in this sector. In dies drilled normal to the 111 plane these stresses, coupled with the thermal, impact and fatigue forces converging in this area, would tend to shear the diamond stone parallel to this plane. Overdrawing and poor operating conditions would of course accentuate this effect and bring it about prematurely.

The previously mentioned dies drilled normal to 110 and 100 planes did not crack in the manner noted above. These failed due to chipping and spalling. Cracks, when present, were small and inclined to the drawing axis. Dies drilled normal to 110 plane have cleavage planes parallel to the die hole axis. In one case a stone drilled in this manner cracked along this plane. Data to date indicate that better die life was obtained from these dies than from those drilled normal to the 111 plane.

The noted studies indicate that the orientation of the drawing hole is of practical importance with regard to stone breakage, the limiting factor of die life. A better understanding of its relation to die performance should achieve appreciable economies. No conclusions have been made as yet with regard to the exact desired orientation of the drawing axis. In Fig. 5 is depicted a unit cube of a diamond structure. Here is shown the possible directions of drilling and the location of the cleavage plane. Figure 6 shows the diamond crystal faces and planes.

Whether or not the aforementioned die breakage characteristics are local to our drawing operations and die sizes is not known. We invite comments from other wire manufacturers whose equipment and practices vary significantly from those used at the Kearny Wire Mill.

Acknowledgment

The author wishes to acknowledge and thank Mr. F. E. Haworth, of the Bell Laboratories, for his x-ray determinations and Mr. W. W. Broughton, of the Quartz Crystal Development Group of this Company, for his many suggestions with reference to the crystallographic studies.

References

1. "Design and Operation of a New Copper Wire Drawing Plant," H. Blount and J. E. Wiltrakis, *Wire and Wire Products*, October 1940. Bell Telephone System Technical Publications *Monograph* B-1273.

2. "Developments in the Manufacture of Copper Wire," J. R. Shea and S. McMullan, Western Electric Company, Inc. Jour. A. I. E. E., Vol. XLVI, February 1927. *Bell System Technical Journal*, Vol. VI, April 1927.
3. Stresses in Wire Drawing (Digest of research work conducted at Sheffield University, England), A. C. Blackall, *Wire and Wire Products*, August 1933.
   Fundamentals of Wire Drawing, F. C. Thompson, Victoria University of Manchester England, *The Iron Age*, October 13, 1908.
4. "Development of Wire Drawing Methods," J. R. Shea, Western Electric Company, Inc. Part three of papers presented at the Hawthorne Works of the Western Electric Company, Inc., Chicago, Illinois, July 10–12, 1929, to the Summer School for Engineering Teachers sponsored by the Society for the Promotion of Engineering Education.
5. A quantitative physical law governing the fall of small particles in various media due to gravity. *Handbook of Chemistry and Physics*, p. 2224, 24th Edition 1940–41.
6. "Manufacture of Quartz Crystal Filters," G. K. Burns, Western Electric Company, Inc. Bell Telephone System Technical Publications *Monograph* B-1253.
7. "Variation of Hardness in the Diamond," E. H. Kraus and C. B. Slawson, University of Michigan, *The American Minerologist*, November 1939.