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A STUDY OF ELECTRIC ARCS
USED FOR DRILLING HOLES

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SUMMARY

A study of the Metalmaster Disintegrator has shown that:

1. The electrical circuit is essentially an a-c circuit that is mechanically rectified. Greater drilling speeds and less electrode consumption are obtained when the electrode is made cathodic or negative.

2. Metal removal is accomplished by an electric arc which heats the metal locally to very high temperatures. This is similar, but on a much smaller scale, to "arc-cutting" as used in the welding industries.

The electrical circuit was changed with the following results:

1. By varying the phase shift, the wear of copper electrode was decreased by a ratio of 3 to 1. Molybdenum electrodes were not affected appreciably by small changes in the phase shift.

2. D-c circuits were not satisfactory because overheating resulted when the arc was not completely quenched.

The following operating conditions for future study are recommended:

1. Vary the frequency by means of a capacitor circuit.

2. Study the effect of cutting fluids and additives to improve cutting speed, surface finish, and metallurgical microstructures.

3. Study other types of machining operations using the best electrical circuit.

4. Investigate residual stresses in forming operations on stainless steel and titanium.

A STUDY OF ELECTRIC ARCS USED FOR DRILLING HOLES

Introduction

This project with the Metalmaster Division of the Clinton Machine Company was originated to study the theory of electric-arc machining and methods to improve and expand the scope of the present equipment manufactured by the company.

A conference was held with Mr. Walter P. Jacobs, General Manager, Mr. Delbert Manchester, Chief Engineer, and Terry Merritt of the Clinton Machine Company, and M. B. Folkert, W. W. Gilbert, and H. F. Poehle of the University of Michigan.

A Model 952-D4 Thomas Metalmaster Disintegrator was furnished to the University for this series of tests. The tests reported here were made by M. B. Folkert in the Electrical Engineering Department of the University.

Operating Conditions

Tests were run on the Metalmaster Disintegrator in order to study the drilling action. Most of the tests were made by drilling holes in 1/2-inch-thick low-carbon-steel test blocks supplied by the company. The electrodes were hollow tubes 0.140 inch in outside diameter and 0.078 inch in inside diameter with a coolant forced through the hollow electrode under pressure. Electrodes of both molybdenum and copper were used.

A working hypothesis of the arcing action was developed which agrees rather well with the test results. The disintegration appears to be due to vaporization of the metal, which is heated by electron bombardment.

If alternating current is to be used it must be rectified. This is achieved mechanically in the disintegrator. Smooth direct current does not produce a good-quality hole because arcs between electrode and sidewall are not readily extinguished. For best results the electrode should be made the cathode and the workpiece the anode.

The Discharge

In order for an arc to be struck, a source of electrons must be available from which electrons can be accelerated across the space separating the electrode and the work. There are two ways of establishing this source. The first is to heat the metal so that electrons are boiled free. The other is to establish a high gradient just off the cathode so that electrons are extracted due to high field emission. We have not attempted to determine which process is actually responsible for the emission but the first seems more logical.[4] This would require either that the electrode actually touch the work lightly on some rough projection, or that impurities in the dielectric fluid actually allow sufficient current to pass into these rough projections to vaporize them. The bridging action seems most plausible. In this case there would be severe local heating of the bridge until the material is vaporized and the bridge disappears. The resultant high temperatures would be sufficient to set electrons free from the cathode.

The heat liberated during bridging also establishes a vapor channel between the electrode and the work. Electrons are accelerated from the cathode to the anode through this channel and some of these electrons collide with vapor particles, causing the particles to ionize due to the impact. Ionization can occur only if the electron has fallen through sufficient voltage before the collision. This is between 5 and 20 volts for most materials.[2] No great amount of current can be passed through the dielectric until ionization occurs. In our tests we found that no appreciable disintegration took place when the peak a-c voltage was less than 10 volts. The small amount of disintegration between 3 and 10 volts is probably the bridge erosion described by Lander and Germer.[4]

The unobstructed flight of electrons through the vapor is about six times as long as that of an ion.[2] Thus the electrons traveling toward the anode collide much less frequently with gas molecules than do the ions moving toward the cathode. These collisions are of two types, those causing ionization and elastic collisions. The elastic collisions, being the more frequent type, are responsible for most of the energy interchange between particles.

When an ion strikes a vapor particle it transfers most of the energy to the vapor particle, but when an electron strikes a vapor particle very little of its energy is transferred. This, coupled with the fact that the ion collisions are more frequent than the electron collisions, means that the electrons will strike the anode with much more energy than that with which the ions will strike the cathode. This suggests making the electrode the cathode and the work the anode. We found that a copper electrode disintegrated six times faster when it was used as an anode than it did when it was used as a cathode.

Discharge Current Densities

In our work with 0.140-inch-diameter electrodes we observed electrode currents of about 60 amperes. Since current flows during alternate half-cycles, the actual current while it is flowing is 120 amperes. Taking the effective area of the discharge to be 0.075 square centimeter gives a current density of 1600 amperes per square centimeter.

Energy Flow at the Anode Surface

The energy flow is indicated in Fig. 1. The anode surface is heated by the energy of the impinging electrons and is cooled by the vaporization of the metal, radiation of heat, convection currents in the gas, and conduction into the metal.

Temperature Rise of Anode and Cathode Surfaces

In order to gain some knowledge of the possible temperatures which can be expected, the rate of temperature rise of the surfaces was calculated neglecting the cooling processes.

Using the current density of 1600 amperes per square centimeter, and assuming that 5/6 of it is due to electrons and 1/6 is due to ions, an electron current density at the anode surface would be 1330 amperes per square centimeter.[3] The potential through which these electrons fall is 10 volts. Under these circumstances the energy delivered to the anode is 13,300 joules or 3190 calories per second per square centimeter. If the specific heat of steel is taken as 0.15 and its density as 8, and the energy calculated above is considered to be delivered to a layer 0.0005 inch or 10^{-3} centimeter thick, it takes only 2.13×10^{-3} second for the temperature to rise 6000°C (10,832°F). In view of this high rate of temperature rise it is almost certain that the mechanism of disintegration is a thermal one.

Carrying out a similar calculation at the cathode surface yields a 1000°C (1832°F) rise in the same length of time. This neglects the fact that ions tend to scatter their energies more than the electrons do. It does show, however, the reason for more rapid disintegration of the anode than of the cathode.

On the basis of these calculations it appears that cathode disintegration might be prevented if the discharge could be moved along the surface rapidly. The calculations indicate that the speed should be of the order of 365 centimeters per second. We have not tried this yet, but Stolt has observed that when an arc cathode is moved at high speed over a metal surface it leaves no trace of melting or burning.[5]

Oscillogram of Voltage

A typical oscillogram of the voltage between the electrode and the work is shown in Fig. 2. The jagged wave shape indicates that the arc is restruck several times during a single half-cycle. Cobine[1] explains this as being due to the convection currents which are present in the vapor under high pressures. The lower half-cycle shows conduction from the electrode to the bottom of the hole. This conduction is responsible for the drilling of the hole. The upper half-cycle shows intermittent breakdown between the electrode and the side of the hole. This is responsible to some degree for the pitting of the sidewalls.

Conduction during the upper half-cycle has been definitely traced to the sidewise vibration of the electrode. This becomes progressively worse as the machine is used. After two months' use, the holes took on a decided elliptical shape. When disassembling the head, it was found that the supporting ball bearings had worn visible indentations into the spindle which holds the electrode, thus allowing the electrode to move sidewise. On rotating the spindle 60 degrees, conduction in the upper half-cycle ceased and the sidewalls of the holes were again of a much better quality. The absence of upper-half-cycle conduction caused no change in the drilling time, which bears out the conclusion that it is only between the electrode and the sidewalls.

Phase-Shift Circuit

A resistance-capacitance phase-shift circuit was constructed so that the instant the electrode comes down on the work can be controlled. Figure 4 shows the details of the circuit changes employed. By changing the values of resistance and capacitance we were able to bring the electrode down at any point in the negative half-cycle. It was found that the best time to bring the head down lies near the beginning of the lower half-cycle. Under this condition the electrode is always the cathode and the work is the anode. This causes minimum energy to be delivered to the electrode surfaces and maximum energy to be delivered to the anode, which reduces the cutting time and electrode wear to a minimum.

The characteristics of the machine as it was received are shown in Fig. 5. Figure 6 shows the characteristics of the machine with the phase-shift circuit adjusted to give optimum performance. Good-quality holes were produced with voltages up to 7.2 volts on the original machine. This corresponds to a drilling time of 400 seconds. With the phase-shift circuit, good holes were obtained up to 10.6 volts, which corresponds to a time of 130 seconds or a reduction in drilling time by a factor of 3.

Figures 7 and 8 show the effect of the angle of phase shift on electrode wear and cutting time for molybdenum and copper electrodes. The higher melting point of molybdenum causes a constant electrode wear over a wider angle than is the case for the copper. Copper electrodes, however, can be made to give comparable performance when the electrode is brought down at the proper point in the cycle as is shown in the figures.

Use of Direct Current for Electrode Voltage

Exploratory tests were run on the use of d-c voltages with both molybdenum and copper electrodes. Although electrode wear was found to be very small and the drilling time was decreased to 90 seconds all the holes were much poorer than those obtained with the original machine. The poor hole quality was probably due to the fact that when d-c was used the arc was never completely extinguished. This prevents the liquid coolant from coming in contact with the hot surfaces of the workpiece. The heat, therefore, is conducted into the metal and melts out large sections.

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5. Stolt, H., Zeit. f. Physik, 26, 95 (1924).

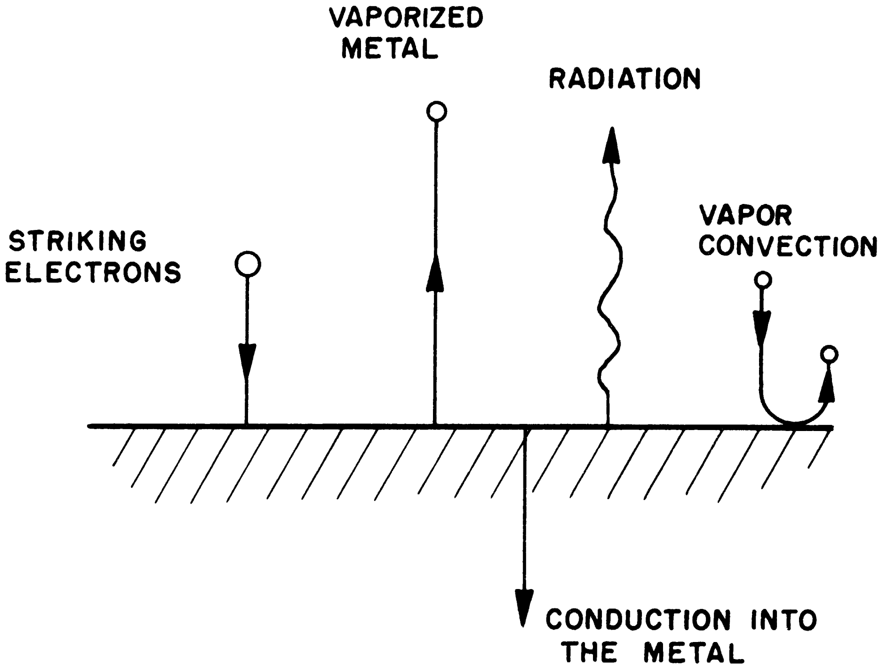

FIG. 1. FLOW OF ENERGY AT THE ANODE SURFACE

USE UNIVERSITY FILE COPY FOR THIS PHOTOGRAPH

Fig. 2. Typical Oscillogram of the Voltage Between Electrode and Work.

USE UNIVERSITY FILE COPY FOR THIS PHOTOGRAPH

Fig. 3. Typical Oscillogram Showing Conduction in the Upper Half-Cycle Due to Conduction Between Electrode and Sidewall.

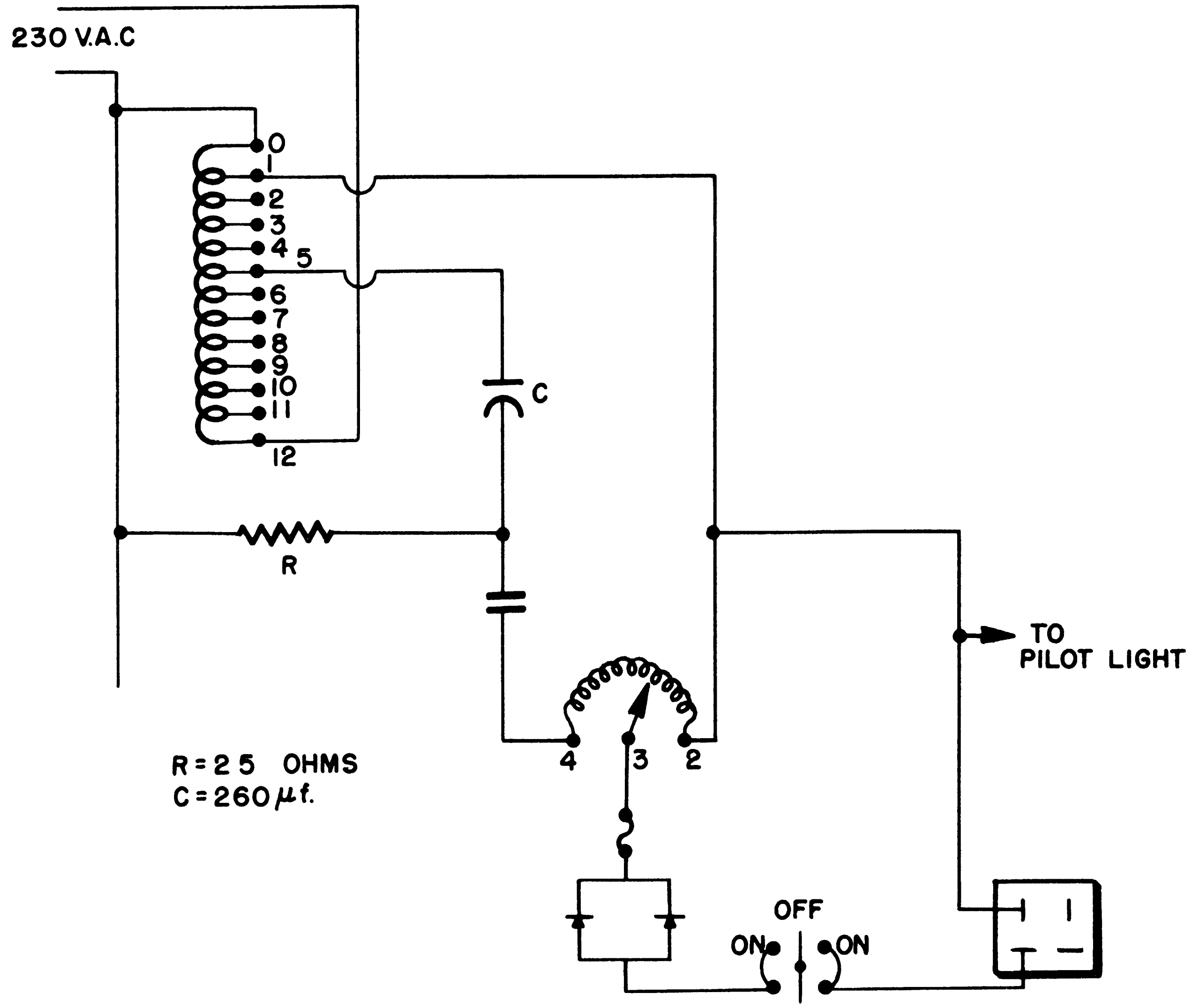

FIG. 4 DETAIL OF CIRCUIT CHANGES TO OBTAIN PHASE SHIFT CONTROL OF THE HEAD

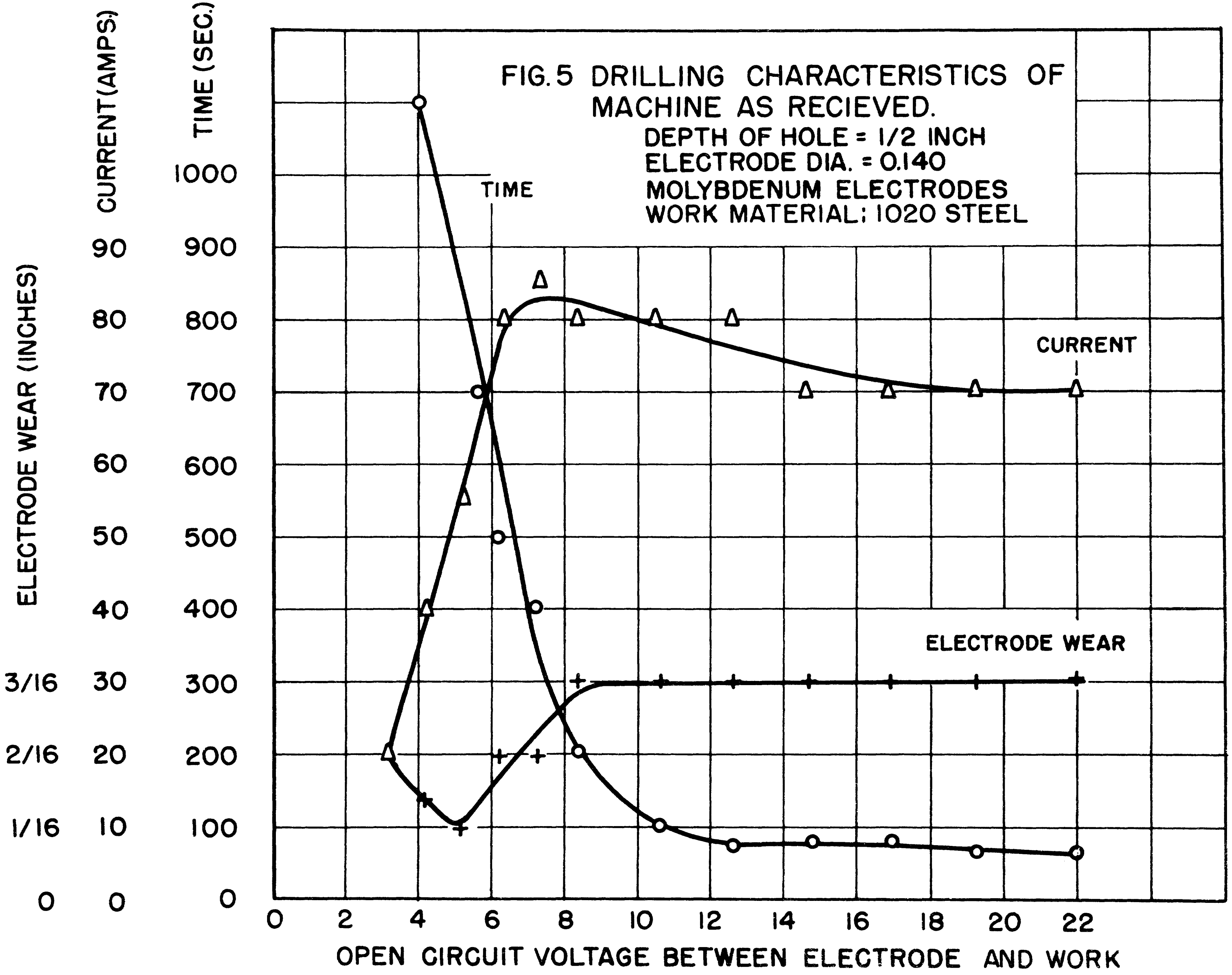

FIG. 5 DRILLING CHARACTERISTICS OF MACHINE AS RECIEVED.

DEPTH OF HOLE = 1/2 INCH
ELECTRODE DIA. = 0.140
MOLYBDENUM ELECTRODES
WORK MATERIAL: 1020 STEEL

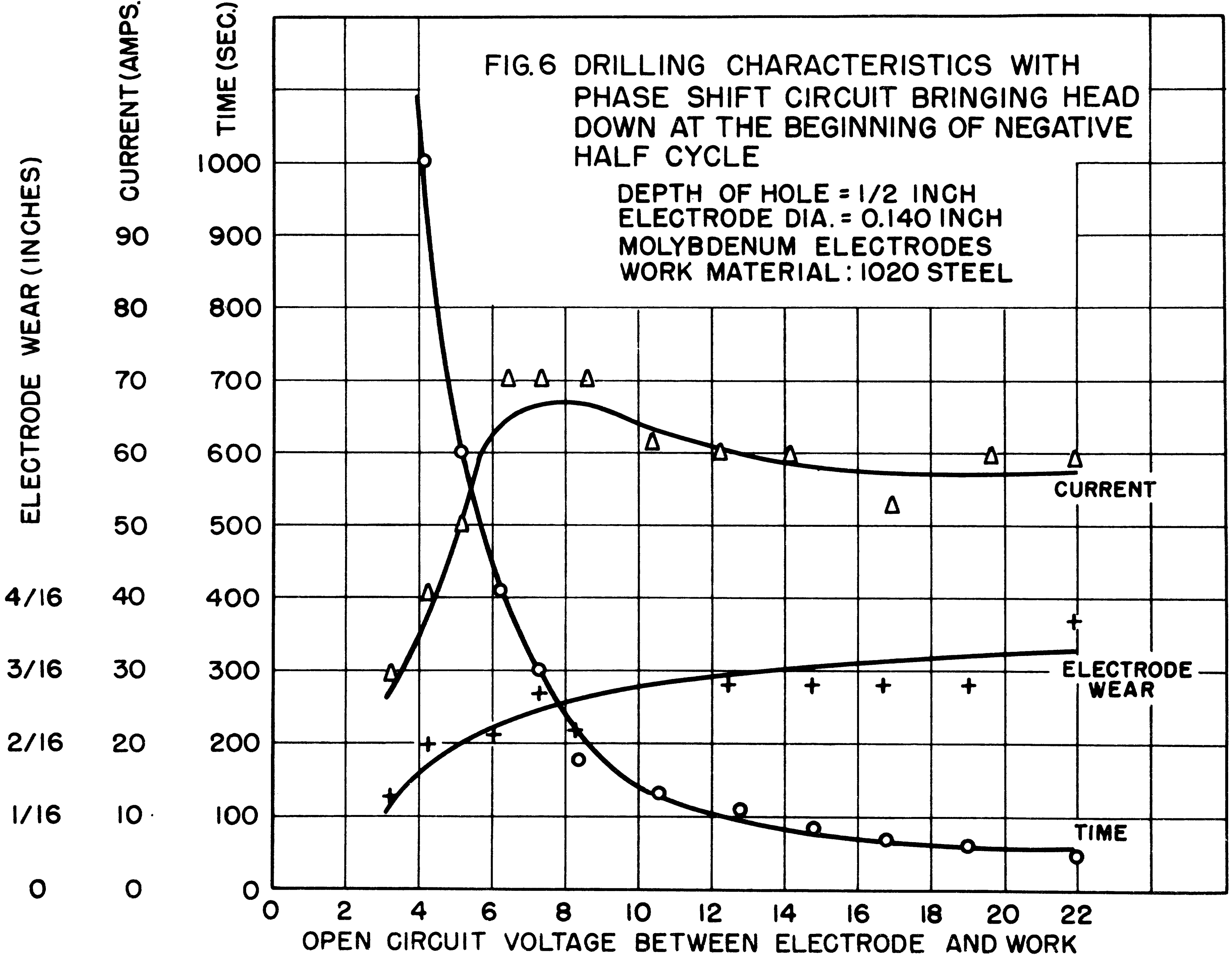

FIG. 6 DRILLING CHARACTERISTICS WITH PHASE SHIFT CIRCUIT BRINGING HEAD DOWN AT THE BEGINNING OF NEGATIVE HALF CYCLE

DEPTH OF HOLE = 1/2 INCH
ELECTRODE DIA. = 0.140 INCH
MOLYBDENUM ELECTRODES
WORK MATERIAL: 1020 STEEL

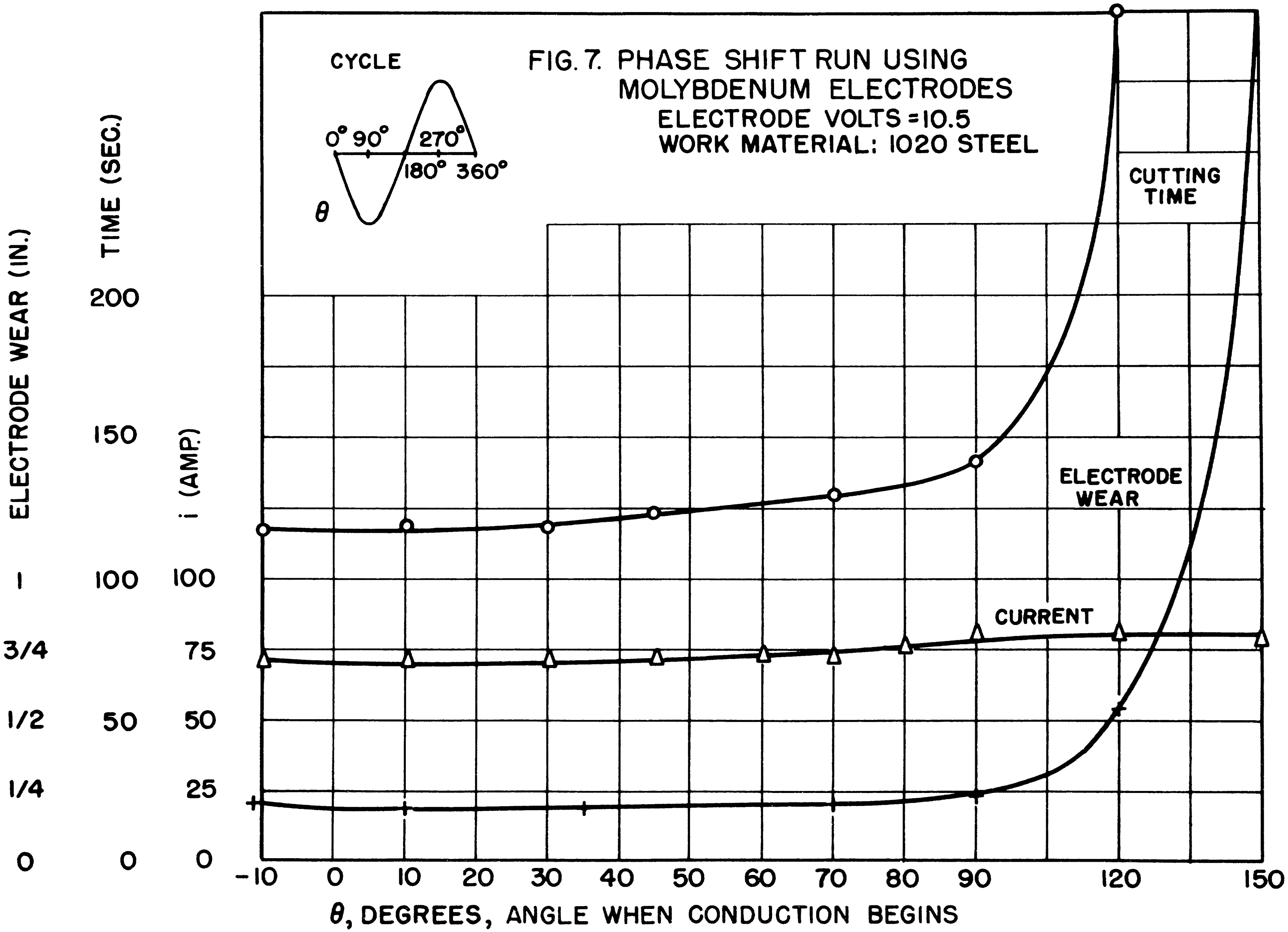

FIG. 7. PHASE SHIFT RUN USING MOLYBDENUM ELECTRODES
ELECTRODE VOLTS = 10.5
WORK MATERIAL: 1020 STEEL

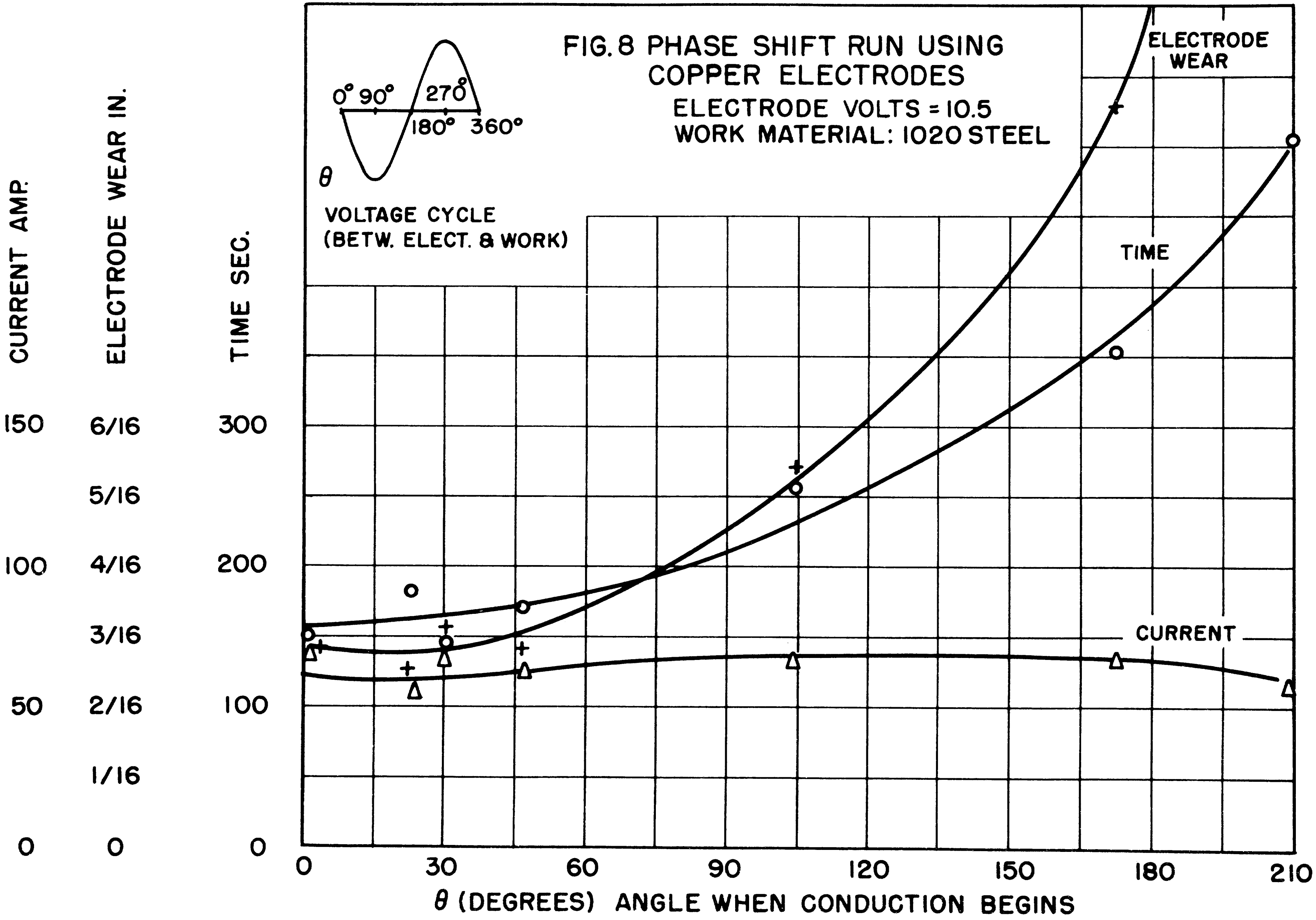

FIG. 8 PHASE SHIFT RUN USING COPPER ELECTRODES

ELECTRODE VOLTS = 10.5
WORK MATERIAL: 1020 STEEL