THE CONTROL OF INDUSTRIAL PROCESSES

Inaugural Lecture of the
Professor of Physical Metallurgy
delivered at the College
on January 22, 1957

by

PROFESSOR A. R. E. SINGER
B.Sc., Ph.D.

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THE planning of an inaugural lecture based on a branch of applied science is always a matter of some difficulty. This is true even at a time when public attention and interest are being turned more and more towards the practical achievements of science. The difficulty arises from the fact that the advance of applied science has been so rapid during the last few decades that a scientist can now play an active and creative part only in a strictly limited field of study within his subject. Quite naturally he would like to show in his lecture some of the fascination of his own work as well as the recent significant accomplishments of his science. But he is always limited in what he can do by the knowledge that the appeal of a science subject to the scientist generally lies in detail and in subtleties rather than in the broad concept. Moreover, he knows that an explanation of detail demands of an audience not only a basic knowledge of the subject but a working knowledge of the methods and even of the technical jargon. The lecturer is generally forced therefore to speak in more general terms.

Amongst many others, one way out of the dilemma is for the lecturer to keep strictly to a general survey and to show in a broad way how the particular branch of science in which he is interested fits into the general pattern of applied science and what its impact has been upon normal day-to-day life. A further way of handling the matter is by means of an historical survey in which some of the outstanding achievements of his branch of study are described. It has the particular advantage of acquiring popular interest but suffers from the disadvantage that it may give little guidance to the way in which current work is tending.

In the present instance it seemed that an approach different from these two was desirable, because a further consideration had to be taken into account. The Chair of Physical Metallurgy was established for the purpose of promoting postgraduate studies and in particular for strengthening research on some aspects of the fabrication of metals. It seemed that, because of the special position of the Chair, a duty devolved upon me to explain the kind of work my colleagues and I in the Department intend to pursue during the next few years. It seemed worth while facing the issue squarely and trying, in the course of the lecture, to outline the principles governing the work we shall be doing, by explaining them in simple non-technical terms. In addition it seemed appropriate for me to give some idea of the kind of practical problems we shall be concerned with and the ways in which the work—if it is successful—may advance our science and perhaps make a small contribution to the prosperity of the metal industry. It is for these reasons that I intend to move on to discuss the subject of the research to which we shall be devoting most of our attention—the principles governing the control of industrial processes. Perhaps I should add that although many of the points I intend to make are of general application to science and engineering, our interest is centred upon the manufacture of semi-finished metal products, and most of the examples will be concerned with metals. My procedure will therefore be first to explain the background of the subject and, in particular, why industrial processes need controlling. Secondly, I intend to examine how processes are controlled—paying special attention to closed-loop control; and finally I hope to be able to show against this background the pattern of the new work we are planning.

Process control

It would be helpful at the outset to give an illustration of what is meant by the control of industrial processes by referring to the manufacture of tinplate, which is a typical semi-finished metal product of great importance in this area. Tinplate is a commonplace material used for making containers and small fabricated articles, from bottle tops on the one hand to baking tins on the other. The reason for its widespread use is that it combines with cheapness the important qualities of strength, ductility, good appearance, and freedom from rusting. The desirable combination of qualities is, in its turn, derived from its composition and mode of manufacture. Basically tinplate consists of steel strip coated with an extremely thin layer of the metal tin. The material that confers on tinplate its strength and cheapness is the steel, whereas the thin layer of tin gives it brightness and resistance to corrosion. Steel strip is one of the cheapest metallic materials, but tin is an expensive metal costing about thirty times as much as steel. The consequences are that, for economic reasons, the steel is coated with the thinnest possible layer of tin consistent with its ability to prevent rusting and confer a good appearance.

The manufacture of tinplate consists of two parts, firstly in producing thin steel strip and secondly in coating the strip with tin. The traditional way of manufacture involved batch or semi-continuous methods of production, but during the last ten years it has given place to the use of high-speed continuous processes, especially in the case of rolling and electro-tinning. There has been a consequent great reduction in the amount of hand labour required and a lowering of the cost of manufacture. The closing of many of the old tinplate mills in this area has in fact been a noticeable feature of the change.

A typical scheme of manufacture would start with the production of molten pig-iron from iron ore by treatment in a blast furnace. The crude iron issuing from the blast furnace is refined in an open-hearth steel furnace and cast to form solid ingots of low carbon steel of the order of 10 to 20 tons in weight. The ingots are subjected to a series of rolling operations first at a white heat and later at room temperature, which together with interposed cleaning, annealing, and joining operations produce a continuous strip of thin steel to serve as a base for the tin coating. Tin may then be deposited on the surface of the steel electrolytically, after which the tinplate is brightened, cut to size, and packaged ready for delivery to customer manufacturers.

With modern equipment all these individual processes are carried out at high speed, either continuously or semi-continuously. Moreover, each process in the sequence uses as its raw material the end product of the preceding one. Similarly the end product of any individual process is the starting-point for the next. If one process goes wrong, or as it is usually expressed, gets out of control, the error will probably not be corrected in the next process and may ultimately lead to an unsatisfactory final product. For the whole of manufacture to proceed smoothly it is necessary that at each stage the individual processes should be controlled to prevent this occurrence. In the simple view, therefore, process control means making sure that each process operates to give a product conforming to a set standard of quality—a standard of quality in fact that will ensure the material is suitable for feeding to the next process.

What has been said so far about the necessity for making sure that the product from each individual process conforms to a set standard of quality is fairly obvious. But until now the surface of the problem has scarcely

been scratched, and by digging more deeply a number of much more interesting features come to light. For instance, it is all very well to discuss a standard of quality, but how is it to be determined and what are the important factors involved in deciding upon it? This is the first point that must be dealt with.

Setting the standard of quality

The process of coating the surface of steel strip with tin can be taken as an illustration of the importance of setting the correct standard of quality. One of the main things affecting the quality of tinplate is the thickness of the coating of tin. Consequently it is essential to be able to stipulate the best thickness for any one particular customer usage.

It can be assumed, other things being equal, that the greater the thickness of tin on the surface of tinplate the higher is the quality. The first consideration is now the value to the consumer, or customer, of the tinplate of various qualities. The criterion of value in the technical sense might then be 'fitness for purpose'. It is of the utmost importance to bear in mind the purpose for which the product is to be used when estimating its value to the consumer. Suppose in the case under consideration the tinplate is used for the manufacture of food containers or food cans. It is apparent that the thickness of tin has a most important bearing on the fitness of the tinplate for this particular usage. In fact a curve might be drawn, as in Fig. 1, showing the way in which value to the consumer, measured in terms of the price he is prepared to pay, depends on the thickness of tin. A thickness of one-hundredth of one-thousandth of an inch of tin confers very little protection, as the tinplate rusts readily even under mild conditions of corrosion. It is clearly valueless for making into food cans. With increasing thickness of tin the degree of protection rises, and one-twentieth of one-thousandth of an inch might give satisfactory service for a period of two years. This would probably be the minimum acceptable standard. An increase to one-tenth of one-thousandth of an inch might enable food to be kept in good condition in store for a period of five years.

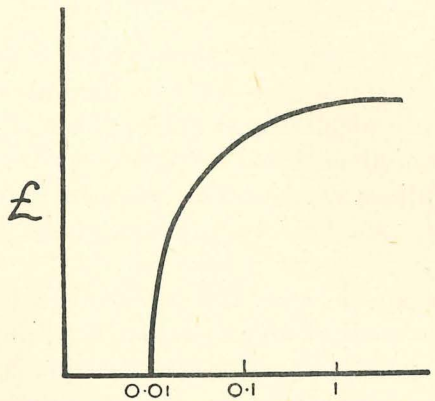

FIG. 1. Value to consumer of tinplate coated with various thicknesses of tin.

The manufacturer of food cans would be prepared to pay rather more for such tinplate. Increasing the tin thickness still further would confer even greater protection and one-thousandth of an inch of tin might enable food to be kept in good condition for a century. However, few people are interested in storing food for a century, and therefore, to the consumer of tinplate for food packaging, this quality is very little greater in value than that with only one-tenth its thickness of tin. In this way it is possible to arrive at a curve showing the maximum price a consumer of tinplate is prepared to pay for various qualities or thickness of tin coatings. The variation of value with quality is shown in Fig. 1.

The other important aspect concerns the cost of manufacture of tinplate of this range of qualities. As mentioned above, tin is an expensive metal costing £700 per ton in ingot form as compared with approximately £50 per ton for steel strip. Assuming other things to be equal, then the cost of tinplate will be the sum of the cost of the basis steel strip and the cost of the tin and its deposition.

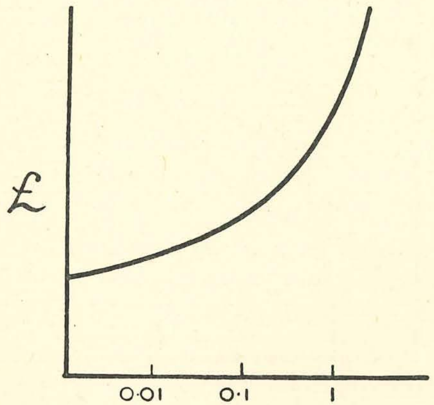

FIG. 2. Cost of manufacture of tinplate coated with various thicknesses of tin.

The curve in Fig. 2 shows how total cost rises with increasing tin thickness. It will be appreciated that there is a basic cost at rather more than the cost of the original steel strip and in addition a rapidly rising cost depending on the thickness of tin deposited on the steel.

Considering both curves together as in Fig. 3, it is apparent that tinplate for food packaging purposes will only be saleable at a profit between the points at which the two curves cross. If the two curves do not cross then no profitable production is possible; and it usually means that an unsuitable raw material has been chosen for making the product. The most significant thing, however, is that there is only one point at which the loop is widest apart in a vertical direction. The point is that at which the possible margin of profit is greatest, or alternatively, at which materials and labour are employed most economically during manufacture and usage.

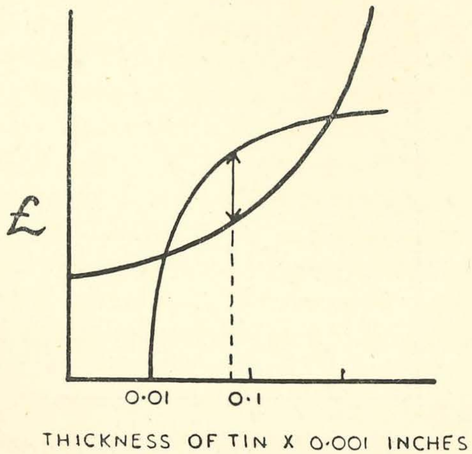

FIG. 3. Combined cost and value curves.

The example is simple but it shows clearly that there is a standard of quality at which it pays a manufacturer to maintain his product. Neither more nor less, because any deviation in quality from this standard either up or down brings with it financial penalties. At first this seems strange because it means in effect that a manufacturer may be making a product of too high a quality—an unusual feature to criticize nowadays! But it is true, for it happens not infrequently that the quality of a product, and therefore its price, is too high for the market at which it is aimed. Thus there is the familiar example of some

consumer goods, especially some of those made in America, that are deliberately produced at a low level of quality entirely suited to the short life for which they are designed.

An example is given by the ubiquitous ball-point pen. At present we seem to be moving towards a time when ease of usage and reliability dictate that a pen is thrown away as soon as the charge of writing fluid is used up. In these circumstances it is necessary to maintain the technical quality of the pen at such a level that the cost of manufacture and therefore the cost to the consumer are not so high as to defeat the primary objective of a dispensable pen. There is, in other words, an optimum quality and cost for the product in relation to its market at any one particular time and at any one given level of technical knowledge. This latter point is of particular importance. It will be observed, moreover, that the factors principally concerned in determining the level of quality are economic ones.

In practical cases the optimum standard of quality is not arrived at by the construction of curves of the type described because the assembly of all the data for both the consumer and producer would be a difficult task. The standard of quality is usually decided experimentally or intuitively. However, the principles involved in forming a judgement are those already outlined and they may in future be used in a more objective and scientific way for making decisions regarding the optimum standard of quality of a product. What is true of consumer goods is true of the product of each individual manufacturing process and it is the most important reason why it is necessary to control industrial processes accurately.

Closed-loop controls

The main problem after having set a standard for the quality of a manufactured product is to find a means of controlling the process so as to make sure the product conforms to the standard. This leads directly into the field of closed-loop feed-back controls. Those present at the inaugural lecture of Professor Fishwick will recall the diagrams he drew showing the way in which such control loops work. The basic principles of the systems are important because they are utilized in a multitude of things in our everyday lives, ranging from the delicate mechanism in our bodies that keeps our body temperature at about 98° F. whatever climate we are in, to the relatively robust regulator control fitted to the ovens of most domestic gas cookers, and, to much farther afield, from the financial control of investments to the automatic pilot of a modern aircraft. As might be expected, closed-loop controls are also of great importance to metallurgical engineering.

In order to explain what is meant by such a control it is best to take a simple everyday example—in this case from the domestic kitchen. It deals with two possible ways of cooking potatoes by boiling. Even though the example is of the simplest possible kind it illustrates all the essential features of control. There seem to be two main ways in which the cooking can be organized. The potatoes may either be boiled for a set period of time, say twenty minutes, or they can be boiled until they are judged by a suitable method of testing and inspection to be ready for eating.

The first method is based upon a general rule derived from past experience which when used with a standard size and age of potato works reasonably well. However, the chief characteristic of the method is that it is blind, in the sense that until the end of the operation when the final product is examined it is not known whether or not the process has been successful. Moreover, if things have gone

wrong, then it is either too late to take corrective measures or the procedure of the second method must be followed.

In the second method a test is applied at intervals during the cooking process—for instance the potatoes may be prodded with a fork; and according to the results of the test the cooking process is adjusted, i.e. it is either stopped or continued. The main feature is that an important property of the product is tested at intervals and the information obtained is then fed back into the system so as to regulate the process. A closed loop is thus formed which includes the examiner or tester and is capable of correcting errors once they have been detected. By using such a system the number of failures is reduced and a much more reliable quality of product is ensured. Moreover, the process is then less demanding as regards the quality of the ingoing raw materials—in this case the size and newness of the potatoes—because it is self-correcting and can make suitable allowances for such variations. With industrial processes the last point is specially important because the stringent inspection of ingoing raw materials means that costs are increased. From a theoretical point of view the two processes, the linear and the closed-loop, are poles apart and the advantages of a closed-loop control are so great that industrial processes should be examined very carefully to see if it is possible to devise any means of benefiting from it.

Automatic gauge control

When metallurgical processes are subjected to this kind of scrutiny, it is surprising what little headway has been made and how few processes have been designed to take full advantage of our basic knowledge of control. The fact that metallurgical engineers are active in at least a part of the field is shown by the way in which the thickness of rolled metal strip is controlled automatically. So far most of the examples have been concerned with non-automatic controls, using a human operator as part of the control loop. The next example is of a control operating entirely by itself, even though the principles of operation are precisely the same as before. The automatic gauge-control system, as it is called, has many variations, one of which is now being installed in a large rolling mill in this district.

One of the most important things to control in the manufacture of metal strip and sheet is the thickness of the product. For most of its useful applications, such as

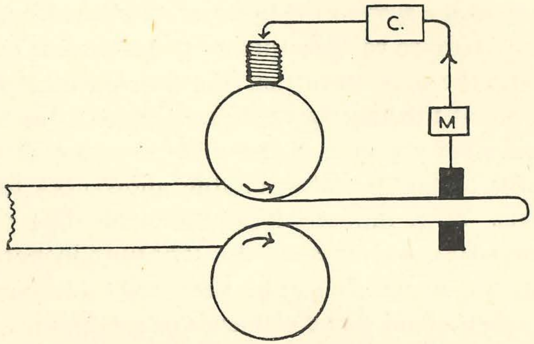

FIG. 4. Rolling mill fitted with automatic gauge control.

that of making motor-car bodies, it is essential that the thickness of the steel strip be fixed and constant along its length, otherwise its value to the consumer is lessened. It is to achieve this constancy of thickness that the automatic gauge-control system, or A.G.C. for short, was devised. Fig. 4 shows in diagrammatic form a rolling mill fitted with the simplest type of control. The important parts of the equipment are the rolls which reduce the metal from a thick to a thin strip, the micrometer (M) which measures the thickness of the outgoing strip, a

controller (C), and the screws which regulate the distance apart of the rolls. In operation the rolls are set at approximately the correct distance apart and the metal is fed through them and between the micrometer, which may be of any type, mechanical or radiation, so long as it allows a rapid measurement of thickness. The signal from the micrometer is then fed into the controller which is set at the desired thickness of the strip, say 0·080 inches.

The controller operates by comparing the ingoing signal from the micrometer with its own standard setting. In general there will be a difference between the two, usually called the error, and the controller in its turn delivers a signal to the screws of the rolling mill according to whether the error is positive or negative. For instance, if the issuing thickness of strip metal is 0·079 inches then the error will be negative because the strip is one-thousandth of an inch below gauge. A signal will be transmitted from the controller to the screws that will cause them to move the rolls farther apart, so correcting the deficiency and the error in the strip passing through the rolls subsequently. The control of course operates in the reverse way if the error is positive. Thus it is a self-regulating closed-loop system by virtue of the fact that a signal concerned with an important quality of the product is fed back so as to alter the process producing the product. There are many design factors of importance, such as the part played by the 'time-lag' which limits its efficiency, but for the moment it is sufficient to deal only with the principles involved in the system.

The main advantage of using A.G.C. is that once the control is set to give a certain issuing thickness then it is maintained despite the fact that the hardness, the width, or the thickness of the ingoing strip may vary. In this respect it is self-regulating and behaves quite differently from a normal rolling mill in which for a given mill setting the product varies according to the ingoing material. The new controlled process improves the quality of rolled strip a great deal as regards uniformity of thickness and increases its value for subsequent use in the making of steel pressings and the like.

The study of process variables

Good progress is being made in the metallurgical industry in adapting to production requirements the ideas concerned with closed-loop controls and the principles are well understood and widely known. In these circumstances it is well worth while proceeding farther to what is at present an almost untouched field in metallurgical engineering. It is a field in which it seems certain that major advances will be made in the near future to improve the quality of metal products and at the same time increase the speed and efficiency of manufacture.

It has been assumed so far that there is no difficulty in recognizing the factors, or the process variable as they are usually called, that it is desirable to control. Such a process variable would be the thickness of metal strip in the last sample. In point of fact, in the metallurgical industry so much attention has been devoted to ways of controlling the obvious factors entering into manufacturing operations that little attention has been spared for any thought as to whether they are the ones it is most desirable to control. Yet it is an important question striking to the heart of the problem. The reason why no careful consideration has yet been given to the subject is mainly that an approach of this kind is quite new to metallurgy. In many cases it involves a fundamental rethinking of a whole process going right back to the basic principles. It means questioning many of the assumptions that had

hitherto been accepted without further thought. It means selecting the process variable it is most desirable to control from the point of view of the process, rather than selecting the obvious ones, that are usually well known and simple to control. Having selected a variable, a means of measuring it has to be devised and finally a means of controlling it.

In many cases such treatment involves the redesign of the process around the means of control. The changes brought about by such a treatment go far beyond a simple modification of existing processes because their very basis may have been changed. In a few cases a redesigning of the type outlined would bring about a revolutionary change. More frequently the process would be outwardly similar, but in operation might be basically different. The point to be stressed is that this work initially involves a reconsideration of industrial manufacturing process from a fundamental standpoint without making any concessions to existing practice. Such work is rightly undertaken by a university department. In fact the freedom of thought and independence of action associated with university study are an immense help in this respect. At a later stage any ideas that have been developed will need to be translated into practical terms in the form of either pilot plant or full-scale working operations. In this case co-operation with industry is essential because the searching test of practical usage is in the end the only criterion of the rightness of design and control of processes.

At this stage an example of the way in which a typical industrial process might be redesigned around the control system would be appropriate. The chief difficulty in giving examples is that very little conscious rethinking of metallurgical processes has been carried out and what little has been done in the way of rethinking and redesigning is mostly too complex to describe in the compass of this lecture. However, an illustration is given by the softening, or annealing process that has to be carried out quite frequently during the manufacture of metal strip. The strip is passed through a furnace where it is heated to a high temperature, when the hard metal re-

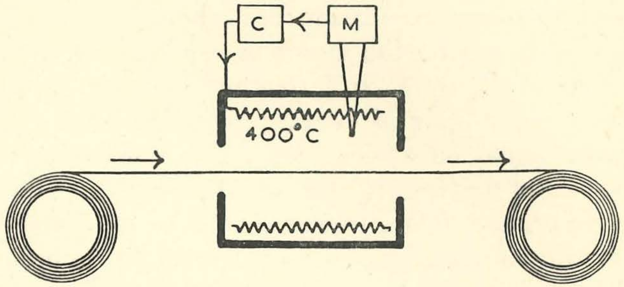

FIG. 5. Annealing furnace fitted with control of a secondary variable.

crystallizes and becomes soft and ready for further operations. In some modern plants it is carried out in continuous annealing furnaces as shown diagrammatically in Fig. 5. Suppose an aluminium alloy that is generally annealed at 400° C. is being processed. Using the normal equipment and technique in industry the temperature inside the furnace would be maintained at 400° C. by means of a temperature-measuring device—in this case a thermocouple—which is connected by a closed-loop control system to the heating elements of the furnace. Such an arrangement would ensure that the temperature of the furnace remained at the correct level, and the strip might be expected to emerge from the furnace in a satisfactorily annealed state. In the majority of cases it does—provided the ingoing material is of the correct composition, its earlier treatment has been carefully standardized and it has been passed through the

furnace at a particular speed. The procedure is a commonly accepted one and immense quantities of metals are treated in this way in industry. It has become such an accepted procedure that it has passed beyond the point at which it is questioned in principle. Nevertheless, some questioning is necessary because the product is not always satisfactory despite good control of the temperature of the annealing furnace.

On further examination it becomes apparent that no property of the metal strip is taking part directly in the control loop. Control is exercised wholly on the temperature of the furnace atmosphere. This may seem desirable as regards the process itself but it is not the purpose of the process and only has an indirect effect on the product. It is true there is a relationship between the furnace temperature and the final properties of the metal strip but it is not a fixed relationship and is subject to alteration by many factors such as the surface appearance, thickness, hardness, &c., of the strip entering the furnace. A process of the type discussed above is one in which there is control of a secondary variable. It is characteristic of such processes that unless the ingoing raw materials are carefully standardized then the product is subject to marked variation.

The control of primary variables

The question immediately arises as to whether it is possible to control an important property of the product directly and so avoid many of the troublesome consequences linked with the control of a secondary variable. In other words, is it possible to control one of the primary variables in the annealing process? The quick answer is that it is usually easier to control secondary than primary variables in the majority of processes. Some advances have, however, been made in the right direction, notably in the case of the A.G.C. system for metal strip mentioned earlier, and in the rapid analysis of steels whilst undergoing treatment in steel-refining furnaces.

Reverting to the example of the annealing of aluminium alloy strip it seems that it should be possible to control during annealing the crystallization and grain structure of the strip, which are two of its most important properties. If an annealing furnace equipped as shown in

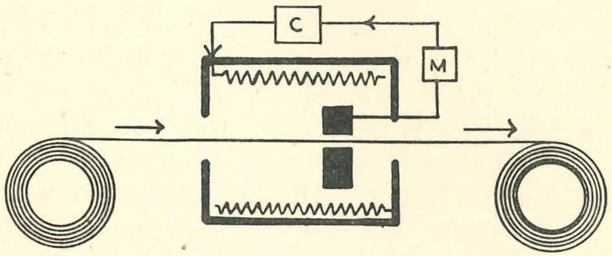

FIG. 6. Annealing furnace fitted with control of a primary variable.

Fig. 6 were constructed in which an X-ray crystal analysis set is built into the furnace together with high-speed scanning and counter mechanisms—all suitably water cooled—then it might be possible to measure and follow the crystallization of metal strip whilst it was still at a high temperature within the furnace. The information could be fed back through a controller so as to regulate the power going to the electric-heating elements of the furnace. Alternatively it could be used to regulate the speed of the strip going through the furnace. In both cases a control loop would be formed which included an important property of the product. It would be a system controlling a primary variable.

The particular advantage of the scheme would be that the quality of the product issuing from the furnace would remain constant irrespective of changes of the

ingoing strip. Moreover, it might be possible to produce partially annealed materials by this method, whereas with the normal furnace arrangement it is a matter of some difficulty. A further possibility is that the speed at which the strip travels through the furnace might be increased a great deal because unlike the existing process there is no limit to the temperature that might be used in the furnace. All in all, the control of annealing furnaces by this means seems to offer attractive possibilities.

It is only fair to add that there are very many problems to be solved not only in the instrumentation but also in the stabilizing of the control that would have to be solved before it could become a practical reality. Moreover, until quite recently it would not have been possible to consider building such a furnace because the high-speed electronic equipment was not sufficiently developed. Even now, as far as is known, no furnace operating on these principles is being developed although in ten or twenty years' time the situation may well be quite different.

Co-operation with industry in research on the control of processes

In the Department of Metallurgy at Swansea it is not proposed to go any farther with this particular scheme because it is of far too great a magnitude for the limited available resources in terms of research workers. Moreover, there are many counter-attractions elsewhere in the metallurgical field which offer greater opportunity for fundamental work on control.

The example of the annealing process shows the kind of thing it is hoped to do with the research team in the Department. Although the problems that will be dealt with are different from those outlined, the general procedure is similar. One or two industrial processes are now being analysed and redesigned in order to control the most significant process variable, and plans are fairly well advanced for the extrusion of metals and for the control of shape in the rolling of metal strip. In each of the two cases work has reached the stage where active co-operation with industry is necessary for the exploitation of the ideas.

The part to be played by industry in work of this kind is most important as is the decision about the way in which work may be divided between the universities and industry. It is essential that work carried out at a university be concerned with the scientific principles of the subject under study, and this view is generally accepted. Yet it must be borne in mind that in conducting research into an applied science it is inescapable that the principles are capable of application to useful purposes. Being useful is not the purpose of the science, but it is a stimulating and highly important by-product. However, before any of the principles can be put to the test of practical application it is always necessary to deal with a great amount of technical detail. The technical detail is inseparable from practical usage; it simply cannot be ignored, and most frequently a decision whether or not to pursue a particular idea rests largely upon it. Moreover, in translating ideas into practical form and discussing them with others a fuller appreciation and understanding of the main ideas often emerges. A further factor is that one of the raw materials for the study of the control of industrial processes is the industrial process itself; and such processes can only be provided by industry even though they can occasionally be simulated in the laboratory.

Thus the part played by industry in the study of the control of industrial processes is a vital one. At the beginning co-operation with the university research worker

for the purpose of discussion and acquiring familiarity with industrial practice is of the greatest value in throwing up new ideas. At a later stage co-operation with industry is essential because the most important laboratory of the metallurgical engineer is the factory and the ultimate test of the rightness of his ideas is in their practical application.

Finally, I would say I believe there is much of basic scientific value in the new study of the control of industrial processes. Moreover, I believe that it offers not only an opportunity for advancing the study of a part of applied science but also an opportunity for making a small contribution of knowledge to benefit the industry of this country on which so much of our future depends.

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