A SURVEY OF METALLURGICAL PROBLEMS IN THE FORGING INDUSTRY

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John F. Lederer

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This is to certify that the

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SURVEY OF METALLURGICAL PROBLEMS
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A SURVEY OF METALLURGICAL PROBLEMS IN THE FORGING INDUSTRY

By

John F. Lederer

AN ABSTRACT

Submitted to the College of Engineering
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THESIS ABSTRACT

Lack of sufficient information pertaining to the forging industry has stimulated the writing of this thesis. It is a review of metallurgical problems pertinent to the forging industry. One of the main purposes of this paper is to stimulate interest in research projects on the part of industry and institutions of higher learning. Areas where research is necessary are specified in each section.

The problems are divided into three areas, namely, heating for forging, aspects of die blocks, and other phases of forging. The heating section includes such problems as overheating, burning, underheating, scaling, decarburization, and rate of heating. Research in this phase of forging embraces improved methods of heating and increased rates of heating, scale free heating (with and without controlled atmosphere), magnitude and effects of overheating, underheating, and burning.

In die blocks, the major considerations are limited compositions available, lack of knowledge concerning wear characteristics, lubrications, and surface conditions, and effects of scale and speed of deformation on dies. Necessary research projects include development of new compositions, study of wear characteristics, improved

understanding of lubrication and surface conditions, and new and improved methods of preparing dies, especially casting the impression in the block and spark erosion. Study of dies through the use of radioactivity is also promising.

Other fields of study are hydrogen embrittlement and flaking, improved understanding of forgeability, including the effects of speed and mode of deformation and conditions of material. New developments entail the use of lead in forgings for improved machinability, forging from the cast state, and investigations of properties and forging characteristics of the vacuum melted and vacuum cast materials.

Fundamentally, the study of these subjects requires increased willingness of industry to allot funds and to cooperate with the institutions of higher learning in arriving at solutions. Progress will advance when all involved exhibit renewed and increased interest in research in forging.

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INTRODUCTION

It is necessary to be acquainted with the entire scope of a process or industry in order to fit its problems into their respective importance. It would be poor economy to exert time solving a problem which occurred only a few times in the production of many thousand pieces in contrast to one which happens with greater frequency.

As the first recipient of the Drop Forging Manufacturers of Lansing's Fellowship, the author was confronted by just such a dilemma. What are the most important and pressing metallurgical problems requiring study in the Drop Forging Industry? Since the answer to this question was not uncovered by discussions or preliminary reading, it was decided that a review of the metallurgical problems was in order. It will be of value to future holders of the Drop Forging Fellowship, as well as providing a comprehensive picture to the people of industry. It is desired that this paper encourage awareness of the scientific metallurgical work required in the Drop Forging Industry.

Kyle defines forging as "the working of metal, either hot or cold, to some definite predetermined shape by hammering or pressing, or by a combination of these processes" (1).* It is one of the oldest mechanical methods in the art of working metals according to the Manual of Open Die Forging (2). Its use dates back many centuries, having been developed with the earliest discovery of metals. Biblical reference indicates that the ancient inhabitants of western Asia were among the earliest users of iron and other forgeable materials. The Greeks and inhabitants of India and China were well versed in the art of hammering metals (3). One of the best illustrations of forging practice was the worlds famous swords of Damascus. The thirteenth century saw the development of the first mechanical hammers using open dies (4). Nasmyth perfected the steam hammer in 1842 (British patent #9382). Many of the original features of Nasmyth's steam hammer are still incorporated in today's hammers, although camouflaged by modernization. With the steam hammer came the application of simple impressions in the die face and the forerunner of the modern closed die process. Many other milestones have dotted the history of forging, including the board drop hammer, trip hammer, upsetter, and forging press to mention only a few.

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* Numbers in parentheses refer to the bibliography.

Today, there are forging hammers rated at 50,000 pounds and larger ones in construction. (The Ladish Company has a counterblow hammer rated by some at 100,000 pounds, but this is controversial.) Two forging presses in operation in this country are rated at 50,000 tons each, with plans almost complete for a 75,000 ton press. A 200,000 ton press is a not too distant reality.

Even with these developments, it has been stated by Bishop (6) "The Drop Forging Industry is not one which readily lends itself to great improvement by research". Others have commented that it is still more of an art than a science. It is with this thought as a spur that the scientific person should proceed into this field which holds so much potential development.

Rather than include a long list of definitions in an appendix, the author has inserted the necessary definitions in the body of the text to insure continuous reading. Complete glossaries of forging terms are available in references (1), (2), (3), and (4) of the bibliography. These are standard reference texts on forging and can be found in any library.

This thesis is in the form of a review of problems existing in the forging industry. All problems are not covered; only those which it appears will benefit industry most by their solution.

In the arrangement of this thesis, the author has attempted to group problems which are closely related into the same section. All problems concerned with heating are in one chapter; die block problems in another. A third chapter deals with a group of problems not necessarily closely related, but still arranged in a logical manner as to importance.

Most of the discussions will pertain to the forging of steel. Where other parts of the industry are specifically concerned; this will be indicated. Many of the remarks will apply to both ferrous and nonferrous forgings even though not specified. Much has been written of the light alloys and titanium due to the government's sponsorship of work in these fields. The inclusion of problems relating to these fields would be a complete thesis in itself. Therefore, only passing mention will be made in this direction.

The problems introduced in this paper are those which should be given first consideration. Their solutions through research and development would enhance the progress of the forging industry.

HEATING FOR FORGING

One of the most important phases in the manufacture of a high quality forging is the heating to forging temperature. Metals are susceptible to many evils while being heated. Among these factors are overheating, burning, underheating, decarburization, scaling, and adverse rate of heating (7). If these factors were kept under complete control, the manufacture of a quality forging would be greatly simplified.

OVERHEATING

Overheating is "A term applied when, after exposure to an excessively high temperature, a metal develops an undesirably coarse grain structure but is not permanently damaged. Unlike a burnt structure, the structure produced by overheating can be corrected by suitable heat treatment, by mechanical work, or by a combination of the two" (8). Since overheating is not a permanent defect, it can be corrected, but special care and handling are required. The difficulty involved is in the detection of an overheated piece. Unless close control is observed, occasional pieces in an overheated condition will be produced. This coarse grained product, with its undesirable attributes and poor physical properties will not be suitable for service, yet will not be rejected in an inspection or test.

Susceptibility to overheating is a function of the chemistry of the metal. It can also be developed by improper heating. Some materials resist overheating and burning in a reducing atmosphere as compared to an oxidizing atmosphere.

Overheating is a time dependent process, and this must be considered in each case, especially those involving complex changes. Generally, high and medium carbon steels are more likely to be overheated than low carbon steels. Although special applications may call for coarse grained steels, their low resistance to shock and greater tendency to distortion are dissuading factors (9).

"The fracture test has become useful to study the effects of forging temperature and overheating on steels, particularly alloy steels" (10). It is quite evident that for the more complex alloys, overheating must be carefully controlled if a serviceable forging is to be produced.

There is no test or procedure whereby a manufacturer can measure the results of overheating. This is an area where quantitative and qualitative information on the degree and effect of time, temperature, and composition should be made available through research. Then, the true effect of these phenomena on the finished forging will be better appreciated.

BURNING

"Burning is defined as heating the metal to a temperature so close to its melting point as to cause permanent injury to the metal by intercrystalline penetration of oxidizing gases, or by incipient melting" (9). The injury which is caused by burning cannot be corrected by any known heat treatment. It may be considered as the stage following overheating. For most materials, burning is avoided by keeping the temperature below a certain maximum. Charts have been compiled for many materials, such as shown in the Metals Handbook, 1948, page 349, which gives the maximum forging temperature to avoid burning.

As in overheating, the detection of burned steel is not readily revealed by examination. Sparking is sometimes visible during burning, but this is not a necessary or sufficient condition for burning to occur (8). Certain metals when used as alloying agents increase the susceptibility to burning (Ni, Co, and Mo), while others (Cu, Si, Cr, and W) have the opposite effect on steels (9). The mechanism and compositions necessary to control burning are known only qualitatively. Resistance to burning is excellent in a strong reducing atmosphere if the carbon content is below 0.84 per cent (4). The same relation as to carbon content exists in burning as in overheating with the higher carbon being more easily burned. Research is needed to determine the effect of time, temperature, composition, and their relative importance on a burnt structure.

UNDERHEATING

The term underheating is self-explanatory. It is used to denote a condition where the temperature is so low that plastic deformation will not proceed without rupture. This defect is not as common as overheating and burning since the hammer operator can often detect it by the manner in which the stock flows under the blow of a hammer. Good furnace control is a valuable aid in keeping underheating in check.

Portevin states "Most hot metals can be deformed to a great extent without rupture or tearing - at least within certain limits of temperature where the material is sufficiently" forgeable or susceptible to considerable deformation without cracking. It is, in short, a tendency toward cracking which limits the scope of these shaping processes, crackability being in a way the reverse of forgeability" (11). Difficulties arise due to a temperature gradient existing in the material. While the surface is in the safe thermal zone of working, the center is below it when underheated.

The theoretical study of plasticity is a comparatively young branch of science and still developing. The rules of plasticity have not been utilized to any great extent in the study of forging. Efforts to apply these rules have achieved only moderate success. The research has been largely concerned with the forces developed from which predictions of the power requirements are made. Little concern has been accorded to the flow of material using the rules which have been developed. This is partly due to their intrinsic complexity. If greater knowledge of metal flow were available, better establishment of both upper and lower limits of forgeability would be possible.

Research on the loss of temperature during forging has developed the following relationship (12).

$$\text{Temperature change } \Delta T = \frac{1200}{S} \text{ in } {}^{\circ}C$$

S is the smallest of the three dimensions in mm. of a piece with a rectangular cross section.

This formula gives the temperature change in a ten second interval when the starting temperature is 1150°C. Only radiation in still air is considered in this case, for if the piece were resting on a steel plate at 300°C, the temperature drop increases by a factor of 1.7.

Research on the plastic flow of metals and the rate and mechanism by which a forging loses heat (en route to hammer, during working, and between blows), similar to that stated above, would provide data to minimize underheating problems.

OXIDATION AND SCALING

The oxidation layer formed on the surface of a metal heated to a high temperature in air or in an oxidizing atmosphere is denoted as scale. Many metals form scale according to the parabolic relation

$$x^2 = kt$$

x is the weight of scale formed, t is time, and k is the rate constant (8).

This equation has been shown valid when a dense and adherent scale is formed. In this case, the specific volume of the oxide is equal to or greater than that of the base metal. The only known exceptions are tungsten and molybdenum. The rate constant k is temperature dependent and may be expressed by the Arrhenius equation

$$k = A \exp\left(-\frac{Q}{RT}\right)$$

A and Q are constants, R is the gas constant, T is the absolute temperature (8).

Those metals with oxides having lower specific volume than that of the metal lose weight by a relation which increases linearly with time (8). The noble metals have oxides with higher dissociation pressures than the partial pressure of oxygen in air at the oxidation temperature, thus forming no superficial oxide.

Oxidation is a diffusion phenomenon. It occurs by an outward movement of metal ions from the base metal, and an inward movement of the oxygen ions from the atmosphere. In both cases, the ions must pass through the already formed oxide layer. The phase diagram of the iron-oxygen system shows three phases - wustite, magnetite, and hematite. The wustite phase is unstable decomposing below 560°C. The accompanying figure shows diagrammatically the manner in which scale appears on steel.

Iron Fe	Wustite FeO	Magnetite Fe_3O_4	Hematite Fe_2O_3	Oxygen O_2
	—Fe —→	←—	—O_2—	
	80-90%	10-20%	.5-2%	

HIGH TEMPERATURE SCALE

Iron Fe	Magnetite Fe_3O_4	Hematite Fe_2O_3	Oxygen O_2

LOW TEMPERATURE SCALE

APPEARANCE OF SCALE ON STEEL (Per Lewis) (13).

In alloy steels the alloying element is often found concentrated in the outer layer of the base metal and the innermost oxide layer. This has been demonstrated when silicon, nickel, chromium, and copper are the alloying agents. Lead is suspected of behaving in a similar manner when it is disseminated in steel for free machining (13).

There is considerable difference in the power of numerous elements to diffuse through the scale. This leads to the conclusion that distribution of the alloying element in the scale is due to the relative rates of diffusion of iron and the element considered.

It has been shown by Wagner that as the electrical conductivity of the oxide decreases, so does the rate of scaling. Since oxides of highest melting point have lowest conductivity, those metals which form these oxides give the best resistance to oxidation when used as alloying agents (8).

The metal composition exerts its influence on the scaling phenomenon,greatly affecting scale composition. It may also cause great difficulty in scale removal (13).

Factors directly responsible for scaling are oxygen, water vapor, carbon dioxide, and sulphur arranged in the order of their relative importance. The reaction of other gases may also assist in the promotion of scale. Small amounts of sulphur gases in an oxidizing atmosphere cause a marked increase in oxidation; also, it is quite harmful in the form of H_2S or organic compounds (14). Sulphur is usually present when gas or oil are used for fuel.

The amount of scale formed on a forging during heating is given as approximately ten per cent of the weight for large forgings, and between two to seven per cent of the weight for small forgings. Work done by Lee-Bird has shown a figure between two to three per cent to be reasonable for small pieces (13,14).

Showalter states "Scale is more than lost metal; it is lost dollars" (15). The effect of scale is felt in many ways such as: 1) lost metal, especially in the expensive high alloy materials, 2) increased cleaning, pickling, blasting, tumbling, and grinding, 3) higher rejection, 4) exceeded tolerances, 5) longer heating times due to insulating value of scale especially on large pieces, 6) unacceptable surfaces, 7) higher machine cost, more finishing passes, more restrikes, and more finish machining, 8) fluxing of furnace bottom, 9) lastly, it shortens die life. This alone is important enough to evoke the remark that, "the avoidance of scale, which is possible with induction heating, offers definite advantages if only in the interests of prolonging die life"(16). This in the face of knowledge that "Scale has a serious abrasive action on dies and punches, but with other factors affecting die wear, it is difficult to assess the exact reduction in die life due to scale" (14). This first quotation is remarkable due to the incompatibility of the above two statements.

English drop forgers consider the removal of scale important enough to warrent its removal before forging. This is done at forging temperatures when no attempt is made to control it during heating. Scraping and brushing are the two mechanical means of removing scale before or during the forging. The applied methods are blowing and spraying. Water at 1500 - 1800 psi pressures has been used successfully and is described in reference 13. Another method used is that of passing the part through an induction coil giving it a rapid thermal shock which removes the scale (17). The nature and effects of scale are well established. The research necessary is that of establishing the conditions where scaling can be reduced to nonimportance.

DECARBURIZATION

Decarburization is "a loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon" (8). As in scaling, decarburization is an effect of heating in an adverse atmosphere. The reactions and types of atmospheres which cause decarburization are well known. As applied to forging, decarburization goes hand in hand with scaling since they are both greatly affected by furnace conditions. Much of the present day heating is accomplished in equipment where little control of decarburization is possible. Elimination of decarburization is not important if scaling is uncontrolled since the scale contains the affected areas, and it is usually removed. It becomes increasingly important to control decarburization when scale is being regulated, especially if a forging relatively scale free of close tolerances is required (ie. induction heating, radiant gas heating, etc.). The opposite effect, carburization, is relatively unimportant, though examples of forging failures by this mode have been described (18). Carbon restoration after forging is demanding more attention as higher strength forgings are being manufactured. Research in decarburization must be along the same lines as in scaling, for these two effects have a high degree of interrelationship.

RATE OF HEATING

The rate and evenness of heating becomes increasingly important as attempts are made to increase the speed of the process of heating. Past experience has dictated preheating and slow heating to temperature to insure a product free of clinks and fine cracks. Also, this was deemed necessary to insure free metal flow during forging. Work done before World War II in England indicated that more rapid heating was feasible. Additional work of more recent origin (19,20,21) has further substantiated these claims by rapid heating with gas using radiation techniques. Some of the advantages listed for this type heating besides speed are as follows: 1) uniform metal temperature 2) little scale formed 3) grain growth is retarded 4) decarburization is reduced and 5) more favorable flow of metal in dies.

The claim of improved forgeability with this rapid heating has not been proved. There is some evidence that a short soak is needed as indicated by some experience with induction heated billets (22).

The main danger of too rapid heating is that of causing internal clinks. These are due to thermal expansion of the outside layer causing stresses sufficient to fracture the interior. Any residual stresses set up in the material by processing to the billet stage prior to reheating add to this effect. Claims made originally by a Polish worker E. Terlecki on rapid heating have been checked by English investigators and found substantially true. The following table shows some of Terlecki's (22) times for heating to 1200°C without clinking. The pieces were charged cold into the furnace at 1350°C.

Heating times for various steel pieces from cold to 1200°C ready for forging (according to Terlecki) (22).

Size (ingot)	Weight	Type of Steel	Heating time (approx.) Hr.	Min.
36 in. dia.	8 tons	0.2% carbon	4	15
30 in. thick slab	12 "	0.2 "	3	20
21 in. dia.	2½ "	18/8 austenitic	2	30
15½ in. slab	2½ "	18/8 "	1	36
7.2 in. dia.	310 lb.	W-Cr. V-Co high-speed	5	40

It is stated that the radiative capacity of the furnace walls depends on the difference between the fourth powers of the absolute temperatures of the walls and work pieces. This is shown by the following formula:

Radiation capacity of the furnace walls $R_c = \left[(T_{fw})^4 - (T_{wp})^4\right]\lambda$

Where T_{fw} is the absolute temperature of the furnace walls and T_{wp} is the absolute temperature of the work piece, λ, a proportionality constant.

Thus, pushing up the wall temperature greatly increases the amount of heat transference to the work. For example, raising the furnace wall temperature from 1100°C to 1400°C would nearly double the rate of heat absorption by the work piece (22). Work by the Selas Corporation of America in heating die blocks has shown that remarkable gains in heating times can be obtained (23). Blocks which took over twenty-four hours to come to temperature in the conventional furnace have been heated in less than four hours.

GENERAL

Before entering a discussion of possible solutions to the above problems, it is wise to review the type of equipment used in the industry. The common heating furnaces in use are as follows: 1) batch furnace - usually slot type, 2) pusher and automatic - conveyer type, 3) rotary hearth furnace, 4) induction furnaces.

In small plants the slot furnace is almost in exclusive use. Larger plants have the pusher type with the induction and rotary hearth (controlled atmosphere) used only for high production continuous runs. The larger plants were careful of the furnace temperature and used temperature controls to regulate it. In none of the small forges visited, did the author see any temperature controls being used. Some operators of the smaller forges spoke of trying controls but with little success, and finally reverted to the age old method of the experienced operator's eye and knowledge. The use of temperature recorders by small forge shops is known to be successful (24, 25). The main obstacle to overcome is that of educating the operators of the furnaces in the use of instruments.

The importance of good temperature control cannot be over-emphasized. Although the forging range of the low carbon low alloy steels is wide, many of the newer alloys have narrow ranges of forgeability. It is important to forge rapidly at the highest possible temperature. Siebel's deformation formula is

$$P = (F)\ (K_f)$$

where P is the pressure required for deformation, F is partial cross section of compression, and K_f is the mean tensile strength.

To take into account losses caused by internal and external friction, the mean tensile strength is replaced by the deformation resistance K_w

$$K_w = \frac{K_f}{N}$$

where N is the forming efficiency.

It is well known that the deformation resistance is controlled by temperature. It decreases as the temperature increases becoming constant in the range 1700° - 2300°F for many steels. Therefore, it is clear that the deformation formula given above is controlled almost exclusively by the temperature. Consequently, if materials are to be deformed easily with minimum wear and tear on equipment, especially on dies, the temperature should be held as high as possible. Therefore, temperature and time at temperature must be closely controlled. Automatic temperature controls can assure these results consistently, whereas, the human operator administers sporadic treatment due to his approximate method. A recent survey by the Drop Forging Association indicates that the furnaces in operation today are running far below their possible efficiencies (26). Only a few furnaces are equipped with preheaters to aid in raising this efficiency. This suggests that a thorough study of operation using temperature controls, with and without preheaters, would yield valuable information as to optimum operating conditions. Establishment of the economy of using heat savers could be ascertained.

Studies of the newer types of heating devices should be made at this time. Induction heating with its many advantages can certainly do a bigger job than it is presently doing. Any process, which offers the following: 1) faster heating, 2) cleaner heating, 3) uniform heating, 4) little scale (increased die life, closer tolerance, less lost material, 5) less decarburization, 6) mechanized (requires unskilled labor), 7) improved surface condition, 8) cool working conditions, 9) compact and adaptable saving space, 10) lower noise level, and 11) little energy wasted, as does induction heating, should be more thoroughly investigated. The main disadvantages are the high initial cost, higher operating cost, and its lack of adaptability for heating various sized pieces. The first two mentioned are offset by the many advantages while the latter can be overcome by development of an adjustable inductor, especially for the small sizes between 1" to 4". These features are illustrated in references 27, 28, 29, 30, and 31.

The newer fast heating radiant gas furnaces (19,20, 21, 32, 33) have recently started to receive their just attention. They have the advantage of low initial cost coupled with speed of heating which reduces the scale and decarburization making them quite attractive for use in forging.

Other promising methods which need more research before they can be adapted to forging are as follows: 1) glass baths such as used in Italy for heating extrusion billets (34), 2) increased use of salt baths especially on larger forgings where the drag out of salt is minimized (35), 3) resistance heating which is considered more economical than most others if successful. The main limitation of this last method is that current has to be fed by contact pieces at the ends. A method has been developed in Sweden using a plastic like sponge which is a good conductor of electricity and may be the answer to this difficulty (22).

A comparison of different methods of heating for forging would be an important step in the solution of heating problems. Factors necessary for consideration would be as follows: Economic status of each method, relative speed, effect on material heated, (especially where speed is high), starting condition of material (ie. with regard to residual stress and shape), and necessary control. With this knowledge, choice of the correct method of heating would be simplified and the means to the production of better quality forging would be close at hand.

A means to evaluate the relative importance of each facet of the forging process is required. Laboratory means for separating the various effects are being developed. C. L. Kolbe of the General Electric Company has developed a technique for forging in an inert atmosphere (36). This allows the factors of heating to be singled out from those of forging by controlling the atmosphere while working the metal. Research similar to this must be made available; then, and only then, will the true importance of heating be put in its proper perspective.

ASPECTS OF DIE BLOCKS

DEVELOPMENT

An important factor to success in the manufacture of a forging is the quality of the die which forms the piece. Modern machining facilities producing superior dies are the secret of success in many small forges. The forge shop is responsible for the care and maintenance (including replacement) of the die following the initial die purchase. This places the burden of research and development squarely on the forging industry if its present competitive position is to be maintained.

The requirements for the die blocks have risen steadily as the magnitude of equipment and tonnage produced has increased. Until 1915, the die blocks in use were annealed carbon steel. After machining they were heat treated (quenched and tempered by color) to the desired hardness. They were usually distorted and had decarburized surfaces. This led to the present day use of alloy steels (23).

Early experience with nickel steels in the prehardened condition led to their modification with chromium. At the same time, molybdenum steels became available and they were developed for use in die blocks. The nickel-chromium-molybdenum and chromium-molybdenum-vanadium are two of the most widely used alloy steels in service today. The alloying agents mentioned increase the strength at elevated temperature and improve hardenability. In addition, molybdenum aids in reducing temper brittleness.

The majority of die blocks are supplied in the prehardened condition. Attempts to produce a free-machining steel in the hardened condition by alloy additions have been unsuccessful. Development of tool steels and carbide cutters has simplified the machining, but the demand for high hardness has exceeded this progress. Hardness values from 55-60 Rockwell "C" have necessitated the use of die inserts, which are hardened after machining, in many of the large hydraulic presses. This is especially true when forging the light metals - aluminum, magnesium, and titanium.

The major characteristics of a good die block are: 1) tough enough to resist work stresses, 2) heat treated and, of such composition to resist softening in service and a tendency toward fire checks, 3) adequate wear resisting qualities, and 4) no internal defects developing after dies are sunk (37). These general features are difficult to achieve in any one composition or alloy. Often the emphasis is on one factor and the others are neglected. The features desired depend on the design of the piece, type of metal and the equipment used for forging (ie. hammer, press, upsetter, etc.).

Sharp corners, quick change of section size, and very thin sections all require special attention and when possible should be avoided. Choice of material has a great bearing on die life. "As a rule, it is the alloying constituents which determine the relative forging ease in producing the part. By increasing the alloying constituents, we increase the forging difficulties and wear on the impression of the dies" (37). Other variables are section size, close tolerances, and heating procedures. With so many changing components, it is difficult to type dies in reference to their wear characteristics.

Dies for aluminum, magnesium and titanium require harder dies to withstand greater frictional wear and permit working to closer tolerances. They are also subjected to higher pressures developed during the plastic flow of the light alloys, especially titanium. Generally, these metals are worked in presses and require dies of a large size. With such large dies, the use of inserts is a natural consequence. It is not unusual to produce pieces over six feet in length with wing spars for airplanes being a classic example. But with such large die blocks, the conditions of laboratory experiment are almost impossible to duplicate. Research for these large dies is being conducted by the forging manufacturers in conjunction with the producers of die blocks. It is true today, as it has been in the past, the largest quantities of die blocks are in smaller sizes. This is an area that requires further exploration. No one source or reference contains the many different compositions of die blocks. Few references, other than manufacturers' literature contain much information pertaining to composition. Some compositions may be found in references 6, 8, 23, 33, and 47. The development of new compositions will always be fertile ground for research.

DIE WEAR

To the question "what is the main trouble with dies?" the layman's probable reply would be "they wear out too fast". Such a simple explanation carries the connotation that the solution is not difficult. Unfortunately, this is not the case. Very little is known of the true factors which cause die wear. Mueller states that "data available on relative die life is based on experience and little is available in written form" (37).

A recent experiment on die wear, based on the generally accepted assumption that during forging, particles of the die are progressively rubbed off the impression surface by the oxide scale (38), has yielded valuable information. It has been shown that radioactive tracers in the form of a plug in the die can be utilized safely. Also, die wear occurs by wearing away the surface. How much is attributed to the forging or to the scale is not clear. Generally, the scale does the damage. Scale examined is always radioactive, and it appears that the rate of die wear is high at the beginning and tapers at the end. These conclusions confirm those of workers in the wire drawing industry using radioactive tracers. This work on dies (38) was done during a normal production run. Trouble was experienced keeping the insert plug level with the die face. In future research, it would seem advisable to proceed on a laboratory scale. Close records should be maintained of the die temperature, and an automatic method to collect scale from the forging by suction should be devised. A metallurgical record of the die blocks used, possibly to the extent of producing duplicate from the same bloom, would reduce some of the variables which add to the complexity of the study. Additional information could be gathered by comparing the normal production to one with a descaled product. Here, the effect of scale free heating versus descaling after heating may be discovered. Further control could be achieved by forging in an inert gas atmosphere as previously mentioned.

A recent study by Jaoul (39) has demonstrated that the radioactive technique can be used on large masses. The piece to be activated is immersed in a radioactive bath (in this case phosphorous 32). The radioactive atoms penetrate into the material, and an analysis shows that radioactivity decreases rapidly with depth. A curve is developed to show radioactivity versus depth, and the determination of the radioactivity at a given point after use of the die will show the amount of metal worn away. Autoradiographs are used to show the areas of die wear and any abnormalities occurring under continuous wear. This method permits precise determination of the location of wear, and autoradiographs can be used to map the relief. These can be calibrated against Geiger Muller tube measurements. This technique is especially interesting because it is nondestructive, and can be applied to large masses to show worn points and any concentration of frictional forces.

German research on die surface shows three zones of wear as a result of die service for a short duration (40). These are: 1) zone of pressure - compressive strains only, no sliding of material along die face 2) zone of compressive and shearing strain and 3) zone of sliding friction - mostly shear strains.

The abrasion, or die wash as it is commonly known, occurs mainly in zones two and three. Dimensional changes can be used as a scale of wear for they are altered in relation to the working time of the dies. A chart showing die wear can be divided into three sections: 1) plastic deformation by compression, 2) die wear by abrasion, and 3) the steady progress is interrupted, die life approaches completion. The final stage is a rapid dimensional change which is a consequence of fatigue or surface cracks together with new plastic deformation.

SPEED EFFECT

That the speed of deformation is an important factor is evident by forging the identical piece the same number of times on a friction screw press and on a hammer. After examination, the wear on the press die was three times that of the hammer die (6). Surface conditions have been investigated in Hanover. Impressions which were hand polished, wet-honed, and shot blasted showed that "disregarding the surface treatment, the die wear was practically the same if the initial surface roughness was less than ten microns" (40).

What the optimum finish is for the light metal dies is a matter for research. Aluminum forms a high melting, very hard, impervious, oxide skin, which is very abrasive to dies. Titanium and magnesium give similar difficulties. These requirements, plus the greater amount of energy required for deformation, creating higher frictional forces, have led to the use of dies with better finishes than in steels. Greater attention must be directed to metal distribution in preliminary forging operation due to the metals' lower plasticity at forging temperature as compared to steels. Titanium in particular with its narrow forging range 900 - 950°C is very sensitive to die finish and design (41).

CHROMIUM PLATING

A layer of wear-resistant chromium plating has been used successfully in many countries to increase die life (33, 40, 6). A twenty to forty micron layer deposited at a current density of forty amps. per sq. dm. is stated to be favorable. Claims of doubling and tripling die life have been made in France (42). Another advantage claimed is that the forging does not adhere to the die as compared to normal conditions. American experience has not led to widespread adoption of this practice. It must be realized that this method will not correct die failures caused by 1) die checking resulting from overheating 2) fatigue cracking resulting from stress in deep cavities 3) fatigue failure due to improper fitting between die and die holder (43). But plating increases wear resistance when wear by abrasion is the main cause of failure. It lends itself well to dies with large areas of flat surfaces (ie. discs, etc.) and has the ability of controlling flash line thickness. A method for detecting the area where chromium plating has worn through is that of coating the die with a copper sulphate solution. Red copper will be deposited on the worn areas while the rest remains steely white.

Judicious choice of the proper die to chromium plate would extend the use of this method. Empirical rules for use include: 1) chromium plate only those dies which show excessive wear at the flash line and 2) chromium plate only where the die sinking cost is greater than twice the cost of two platings (43).

The future development of this technique depends on: research to develop a means for measuring the relative extension of die life over a normal life, better establishment of the type of die for plating (ie. use on hammer or press, shape of piece, etc.). Along with this program, thought should be given to other types of surface treatment. In this category are: surface hardening by diffusion processes (nitriding, etc.) weld facing, high heat treated hardnesses, peening, and others. But, it should be emphasized that unless a suitable method is developed, which will allow for proper evaluation of these processes, all work will be of secondary value due to lack of concrete proof.

LUBRICATION

Another avenue of approach is the question of lubrication. Here, again, little written knowledge exists. As one author states "the choice of die lubricants has evolved through habit or tradition or pet idea of the hammer operator" (44). The primary uses of a lubricant are: 1) reduce friction and wear, 2) assist metal flow, 3) prevent welding and seizure by formation of a protective coat on the impression, 4) facilitate removal of the forging from die cavities, and 5) serve as a coolant (long production runs) (44, 45).

The mode in which stock is assisted in removal from the die is thought to be: as stock is forced into the cavity, oil is instantly gassified and enough pressure is formed to eject the forging from the die. It is claimed that fire checking is a result of the explosion of oil, but no proof is available.

The characteristics of a good lubricant are: noncorrosive and nonstaining to work and die, convenient to handle, mix, and apply, stable in service, readily cleaned from work, nontoxic and economical (45). With this large number of functions to fulfill, it is no wonder that a universally suitable lubricant has not evolved. In fact, there are forge shops in operation which use little or no lubricants. Many use the mixture of colloidal graphite in water, commercially available as "aquadag". The dies are pretreated in the die shop, and the coating is maintained by spray or dabbing of a dilute solution in service (46). Other lubricants in use are: 1) plain oils, 2) cylinder oils, 3) fuel oils, 4) black oils, 5) peanut oils, 6) vegetable oils, 7) powdered coal and oil, 8) soap and water, 9) salt-water, 10) sawdust, and 11) graphite in oil (44). With so much deviation, it is clear that development on the aspects of lubrication should precede any scientific choice of a lubricant.

FINISHED IMPRESSIONS

Discussion of dies would hardly be complete without some mention of the newer methods of producing finished impression die blocks. The method which many people consider to be the most promising is that of electric spark erosion. It consists in breaking the material out of the die by means of electric sparks. Whether this can produce dies of proper finish and tolerance to justify replacement of the standard die sinking equipment is a question for the future (42, 47, and 33).

A possibility which has been considered for some years, but is still undeveloped is that of the cast die block. The knowledge developed in Germany of the casting technique to an extent where the cost compares more than favorably with the forged machined product should be proof enough of its applicability (33). This is especially true where large blocks with limited runs are required. Castings should also lend themselves for use as inserts

Data gathered after the war revealed unique techniques for making cast die blocks at Ruhrstahl in Annen for propellers, propeller hubs, and crankshafts. The composition of the die material was carbon .45 -.55, manganese 1.2 - 1.5, silicon .45 - .55, chromium 1.8 - 2.0, and vanadium .20 - .22. Heat treatment included heating to 1580°F and quenching in oil. Dies were tempered to the desired hardness usually a range from 900°- 940°F. The Witten Forge in Ruhrstahl used only cast die blocks in its operation (48). The development of cast die blocks is a field with great promise. Research by Dixon indicates that "high pressure with no appreciable plastic flow has shown a material improvement in ductility of ingot material" (49). It is possible that this type of reasoning may be used, to improve, without appreciable deformation, the ductility of cast die blocks.

That cast blocks would ever fully supplant the forged machined block is unlikely, but they could provide a valuable adjunct to the machined dies. Their use on short runs would be a decided advantage. Press dies with their lower impact requirements would be a natural starting ground. Use of the new vacuum melted and cast materials may prove to be a valuable advancement in the casting of dies.

Use of beryllium copper for cast forging dies in the forging of light metals has developed in the last few years. In England, they are being produced by cement mould casting and supplied overaged to approximately a hardness of 35 Rockwell "C". No exact determination has been made of die life. Some steels have been successfully forged using these dies. Most of the tests conducted to date have utilized beryllium copper dies as inserts backed by steel retainers. The primary reason for the choice of beryllium copper is its excellent casting properties which eliminate machining required on steel dies. These dies can be remelted when they become worn or obsolete with the addition of some virgin alloy to produce new dies (50). How well adapted these dies are for hammer operation is unknown. A fruitful field for research is the future of beryllium copper cast dies.

In the solution of many of the above problems, it is advisable that a practical approach be pursued as distinct from a purely scientific treatment. This will aid in enlisting the cooperation of industry in achieving solutions which will be of practical as well as academic value.

OTHER PHASES OF FORGING

FLAKES AND HYDROGEN EMBRITTLEMENT

"The phenomenon of embrittlement of metals by gases has long been a problem in the metal industry and seems to re-occur as an unsolved problem at various times" (51). The first evidence of this type failure occured in 1911 and again in 1915 when railroad accidents resulted from the break of rails. Early investigators described them as transverse fissures. As the service requirements of railroads increased, so did the rate of failures. Later, this type of phenomenon was discovered in forged and rolled steels where it acquired the name of flakes or shatter cracks. In Great Britain, it was named hair-cracks or hair lines, while Germans called it flocken and the French ligneuses (9). The Metals Handbook defines flakes as "internal fissures in ferrous metals. In a fractured surface these fissures may appear as sizeable areas of silvery brightness and coarse texture; in wrought products such fissures may appear as short discontinuities on an etched section" (8). There is not complete agreement on the characteristic of course texture for many observers have described flakes as silvery bright. Since smooth surfaces are highly reflective, this indicates that parts of the area within flakes must be smooth. In Zapffe and Sims's description of flakes, they mention flat reflecting facets as the course which the break followed (52). This is in agreement with the conclusion of smooth surfaces constituting the fracture.

Another characteristic of flaked steel is that a tensile test bar will develop full tensile strength and elastic limit, but it will show low ductility and reduction of area (9). The correlation between ductility and hydrogen has been confirmed on some low alloy steels. Hydrogen had little effect on the stress strain curves, but fracture occurred before elongation and reduction in area reached normal values. The report concludes that hydrogen content alone does not determine whether hair line cracks will form, but it is a major factor (53).

In 1935, Musatti and Reggiori discovered that flakes in steel could be produced by introduction of hydrogen into the steel (54). Related research revealed that speed of diffusion of hydrogen in steels showed a marked discontinuity between 350° - 500°F. It suddenly decreases about 300 per cent. Thus, the metal passes from a permeable state to one of relative impermeability, due to the abrupt drop in the rate of diffusion. This led to the postulation that hydrogen was the cause of all flakes. An explanation of the mechanism is that a larger quantity of hydrogen would be absorbed at high temperatures than necessary to cause a bursting pressure at lower temperatures. When cooled quickly, the metal reaches a temperature where it suddenly becomes impermeable. The hydrogen develops all its pressure locally and flakes are formed.

Cramer (55) in 1937 concluded that no relation between gas content, microstructure and flakes existed. He postulated the hydrogen being liberated is trapped in the interior of the steel and collects in minute spaces around inclusions and other small voids. Thus, pressures are developed over small areas and exceed the ultimate strength of the material. He explains a number of ways in which hydrogen enters molten steel with the most important being production of hydrogen during combustion of fuel in the open hearth.

Zapffe and Sims (54) found that other factors besides hydrogen had an effect on the formation of flakes. They found the relationship between internal stresses and many of the different microstructures (fisheyes, snowflakes, etc.) was not at all clear. In their article, evidence and support of the theory that steel is composed of sub-crystalline structures, called blocks, is outlined. The authors believed that the network of disjunctions which give rise to the identity of these blocks is the place where hydrogen occludes. Pressure is built up and these disjunctions are sprung. The block theory also explains the bright fractures noted which are considered as due to the favorably orientated group of blocks across which the break proceeds. They consider the occluded hydrogen as imposing a triaxial aerostatic stress state. Materials stressed in this manner cannot flow; they respond only by rupture. Snowflakes, fisheyes, white spots, birdeyes, snake eyes, rosettes, and silver streaks are hydrogen embrittlement localized about some interstice, inclusion, or blowhole. Flakes are considered to be hydrogen embrittled zones which have cracked from internally imposed stresses. Lastly, it was found that embrittling quantities of hydrogen are most rapidly removed from a low carbon steel at a temperature just below that of the lower critical.

Fast (51), in discussing the mechanism of diffusion of gases in metals, believes that it is the surface effect, and not the diffusion itself, which is the deciding factor in diffusion velocity. Because of the diatomic character of the gases, in considering permeability he lists five stages in the penetration of gases through metal walls. They are: 1) dissociation of molecules into atoms or ions at the surface of entry,2) penetration of the atom or ion into the metal,3) diffusion in the metal, 4) transition from the dissolved to the adsorbed state at the exit surfaces,and 5) reassociation of the components into diatomic molecules. The speed of the whole permeating process is controlled by the slowest of these five stages.

Kingsley (56) in 1945 outlined some factors in the formation of flakes. Some of these are: large pieces are more prone to flakes than small ones, some steels of high carbon high alloy content are more susceptible than lower analyses, different heats have different degrees of susceptibility to flaking, and some heats required a germination period after reaching room temperature, occasionally developing flakes six months after production. Austenitic stainless grades do not develop flakes although sufficient hydrogen is present to cause bleeding during solidification. The author outlines a cooling cycle to avoid flaking as well as giving his reasons for the formation of flakes. His reasons are: 1) thermal stress,2) hydrogen pressure,3) stresses caused by phase change during cooling,and 4) residual stress from hot working.

In 1947 a number of determinations of hydrogen content in plain and alloy steels was made by Sykes, Burton, and Gegg (57). They demonstrated that reduced ductility was obtained with as little as 2 cc per 100 grams while the hydrogen content of a normally produced steel was 4-6 cc per 100 grams. In studying heat treatment effects on hydrogen content, it was concluded that relatively high hydrogen contents do not automatically lead to hair line cracks. But, there is no doubt that hydrogen rich material is more prone to cracking during heating and cooling. Also, predictions on the rate of loss of hydrogen content were made. These were based on certain assumptions of permeability and solubility.

Koehler and Wishart (58) working on the theory that shatter cracks could be welded together after formation, found that orientation controlled the welding of shatter cracks (62). Those with unfavorable orientations would not weld and often became exaggerated after working. Their position also influenced the amount of work necessary to weld these cracks.

Andrews's study of the relationship between crack formation and embrittlement established that they are closely associated (51). Embrittlement requires less hydrogen than required for hair line crack formations. This was based on the theory that crack formation is due to "disruptive hydrogen pressure being built up in internal cavities or voids" (51). Any imperfection in the lattice which would hold more than one hydrogen molecule would cause this pressure. It was also suggested that the reaction between hydrogen and iron carbide might create a pressure of methane sufficient to rupture the lattice. But the main emphasis of the study was that hydrogen diffusivity and solubility are the two main factors determining the behavior in any specific instance. Only when the effect on structure and stresses of these factors is known, will the full understanding of the phenomenon be reached.

This led to work by Chang and Bennett (59) on the effect of a chromium, nickel, and molybdenum on the rate of hydrogen permeation. Chromium was found to have little effect in the gamma range while it greatly reduced the rate in the alpha range. Nickel and molybdenum had little effect on either. These authors re-examined the permeation equation and developed a more general equation from experimental evidence.

A discussion on the hydrogen phenomenon on the basis of internal pressure by Andrew and Lee (51) reveals the modern conception. The hydrogen at high temperature, retained in the lattice in atomic form, is in solid solution. Lower temperatures cause it to be precipitated into crystalline and crystallite boundaries. These pockets of occluded hydrogen in molecular form, which make further diffusion impossible, create internal stresses in the metal. This concept of molecular hydrogen concentration at lattice imperfections (crystallite boundaries) explains why composition and thermal history of the steel control the amount of hydrogen.

The present techniques for controlling the presence of flakes in forgings other than by heating, are as follows: 1) new steel compositions, 2) improvements in steel making, ingot casting, and ingot mold design, 3) modification of forging practice coupled with intermediate heat treatment, and 4) improved ultrasonic testing methods.

It must be realized that as the size of the forging increases, the metallurgical problems associated with the hydrogen embrittlement and flakes also increase. Catastrophic failures, one of which occurred in Chicago (60), are directly attributed to hydrogen embrittlement and must be avoided at all cost.

To date, it has not been possible to tie down the exact role of hydrogen in the formation of flakes. Hydrogen content alone is not the determining factor as to whether cracks will form. While hydrogen is a fundamental cause of flakes, it is affected by other factors, especially stresses. These are important in the effect they have on diffusivity and solubility. Research at this time should be on hydrogen diffusivity and solubility under various conditions. The effect of structure and stress upon these factors must be thoroughly understood. Then, the controversies regarding cause and mechanism of flakes and embrittlement will be settled.

FORGEABILITY

"There are few publications dealing with laboratory tests for hot workability" states Hughes in 1951 (61). Tests which have been developed, with references giving descriptions and uses, are as follows: short time tensile test at high temperature (62), notched bar impact test at high temperature (62, 63, 64), static hot bend test (62, 64), hot twist test (61, 62, 64, 65, 66, 67), and single blow drop tests (62, 64, 68, 69, 70, 71, 72). Most investigators favor the hot twist test for evaluating the forging characteristics of steels. A great deal of quantitative data on various steels using the hot twist test is available in references 65 and 66. This test yields good correlation with hot piercing operations. The hot impact test is useful in studying the effects of grain size, inclusions, segregation, and similar effects on malleability. The drop test is often used to compute a rough estimate for the power required to deform a material.

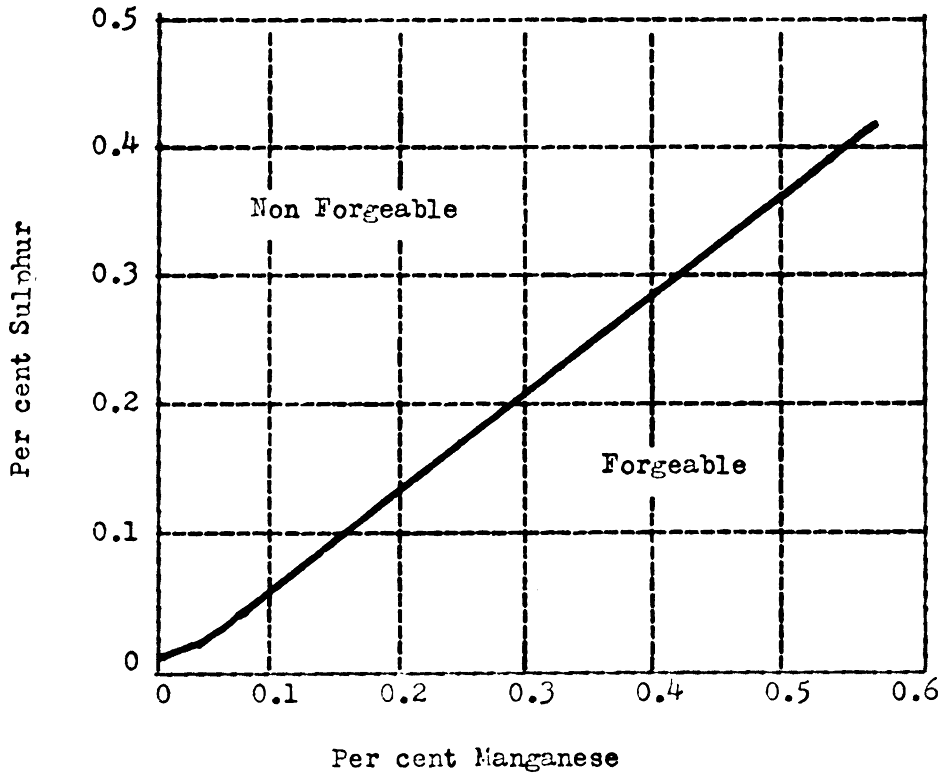
These tests, after suitable manipulation, can be used to show the effect of composition and constitution on hot workability. They indicate the likely hot working temperature and critical nature of this temperature. Their use for comparing the hot workability of an unknown versus known is obvious.

As a first approximation, these tests can be used to compare the forces required to deform different materials at various temperatures to indicate how power requirements will change. Tests of this kind on incoming heats of steel can help to reveal anomalous hot working properties. Development of new tests, which show better correlation and improved use of the present tests are necessary research projects to further the understanding of hot workability.

Forgeability depends on 1) factors pertaining to the metal being worked, (ie. composition, grain size, freedom from inclusion or segregation, etc.) 2) factors depending on operating conditions - particularly the temperature of the metal and the speed and mode of deformation, 3) condition of surface of ingot or billet (which depends on other operating conditions (ie. furnace atmosphere, tool lubrication, etc.). There is a thermal range or safe margin of temperature wherein hot working under definite conditions is possible. The degree of constraint imposed on the metal during working has a great influence on forgeability. Since metals are practically incompressible, they break under tensile stress or slip due to shear stress; deformation under compression constraints is most favorable (11).

Lack of fundamental knowledge concerning the exact effect which each of the many alloying agents has on the hot working characteristics of steels indicates the necessity for research in this field. A discovery in 1951 that "The rare earths are an effective agent in promoting and improving the hot workability of austenitic chromium, nickel, and high alloyed stainless steels when added as an alloying element" (73) is a step in the right direction. This has enabled the discoverers to convert a nonworkable steel to workable and also to improve the hot workability of other compositions. Cerium and lanthanum, elements commonly associated in mischmetal, are the principle agents in use. The range of rare earth metals was found to be narrow and critical at any given nickel content. The exact mechanism in promoting hot workability is unknown and the range of analyses has been determined by experiment. Research must be done to establish the true effect of this alloying addition.

Anderson, Kimball, and Cattoir (74) have found that a relation between manganese and sulphur in certain iron-carbon alloys is a critical factor in hot workability. Manganese free steels with more than .017 per cent sulphur cannot be hot forged. Decreasing the sulphur to .010 per cent improved the hot working properties and when it reached .002 per cent the steels exhibited excellent hot working properties. Later work (75) revealed the quantitative nature of these elements on hot workability. The figure on the following page reveals this relationship.



EFFECT OF MANGANESE AND SULPHUR ON FORGEABILITY (Anderson, et al) (75).

Sulphur is the principal impurity which affects hot workability. The role of manganese is that of a desulphurizer and deoxidizer and alloying agent. The amount of manganese needed is given by the following formula which holds for above .03% S and .06% Mn

%Mn required = 1.25 (%S) + .03

It was found that varying the carbon and aluminum (used for deoxidizing) had no effect on hot forgeability.

Ihrig (66) has made a list showing the qualitative effects of various elements on the hot working characteristics of steels. The following table shows these effects.

Little or no Effect	Beneficial Effect	Detrimental Effect
Oxygen	Manganese	Sulphur
Carbon	Nickel	Selenium
Phosphorus	Chromium above 9%	Silicon
Cobalt		Nitrogen
Vanadium		Molybdenum
Titanium		Columbium
		Lead
		Tin
		Chromium below 9%

EFFECT OF VARIOUS ELEMENTS ON
HOT WORKING CHARACTERISTICS (per Ihrig) (66).

It is interesting to note that in all these investigations of hot workability, the hot twist test was used as a measure of hot working.

These studies show the necessity for research on the many minor constituents to determine the quantitative effect of these elements on the forgeability of steels.

Clark (65) recognized the fact that "deformation characteristics and path of fracture in steels is a function of temperature and rate of application of stress". Using the hot twist test, in which the rates of deformation were of the same magnitude as in forging, he found that the material which failed above the maximum given by the twist test did so by intercrystalline failure. Also, the rate of deformation was no longer critical above a certain rate.

Sachs (76) states that "a very pronounced, but comparatively simple, speed effect exists in the temperature range of true hot working. The higher the speed, the larger is the flow stress, while the ductility is generally unlimited and no hardening is retained after forming." He states further that in reference to the magnitude, if the forming velocity is doubled, the resulting flow stress and forming forces increase about 10 to 20 per cent. This simple relation allows a test to be conducted at slow speed. After adding a certain amount to account for the difference in speed between the test and the actual process in estimating the force and power required for a particular operation, the experimenter should have a conservative estimate. This is due to the temperature increase of the part when formed at high speeds.

The flow stress or resistance to deformation decreases as the temperature increases. At any given temperature, it will tend to level off in value. In general, it has a higher value under dynamic than static loading. It also increases as the speed of deformation increases. Reference 64 presents graphs showing this effect. Ellis (71) demonstrated that grain size has a minor effect on deformation resistance. The fine grained steels have greater resistance at forging temperatures.

Impact effects also enter into consideration in forgeability. Under static loads, the stresses follow known rules. In rapid force application, the relation is more complex. Sachs (75) distinguishes two periods, an initial and stationary period, under such conditions. The stationary period, in which there is no acceleration or deceleration follows the laws of mechanics for stress prediction. It is during the initial period, when the velocity is changing that no rules for stress distribution have been advanced for plastically deformed materials. When the fast moving tool collides with the work, energy is released by the tool. It is dissipated in two ways;

some goes into deformation of the equipment, and the rest into plastic deformation of the metal. The energy deforming the material accelerates the particles near the surface where the tool and piece contact, but this effect diminishes with depth of pentration into the piece. Very high stresses occur at the surface in the initial period during the forming operation. Consequently, the higher the velocity, the more the deformation will be concentrated at the end of the forming period. In forging, if the blows are light and fast, the deformation will be concentrated near the contact area, while with a slowly applied load, the deformation is uniformly distributed.

Cook (77) has studied the effect on the mode of deformation. He considered these aspects: a) the effect of tool geometry and forging schedule on the mode of deformation and strain distribution within forged stock, and b) the extent to which mechanical properties are dependent on forging strains. His results show clearly that tool geometry is important, and that inhomogeneous strains can lead to variations in mechanical properties. This article concludes that plasticine models can give quantitative results on the measurements of strains in the interior of forged models. These results can be correlated with that of steel, for proof is given that plasticine is a satisfactory model for steel at forging temperature.

It should be clear that the use of plasticine models in research can aid in giving the necessary information needed to clarify the effects of speed and mode of deformation. This is the direction for research if progress is to be accomplished in understanding these effects.

OTHER POSSIBILITIES

Recent advancements in the technique of adding lead to steel have resulted in a better distribution of lead in ingots (78). Lead gives improved machinability by allowing faster removal of metal by deeper cuts and faster operating speeds. The possibility of using lead in forgings seems an obvious procedure. Reevaluation of this technique is a research project worth time and talent.

The dependability of a forging is based to a large extent on the planned directionality of flow lines in the forged part. Grain flow is inherent in the forging and is retained regardless of subsequent heat treatment.

Flow lines impart improved ductility, and impact strength in a direction parallel to their course in the forging, while these properties perpendicular to flow lines are reduced. They are macroscopic and can be developed by simple polishing and etching. This fiber developed by etching has an unknown origin.

Many people believe that fiber is chiefly the extension of constituents in the metal, both metallic and nonmetallic, in the direction of working. Others believe flow lines are connected with dislocations. No definite proof is available for either view. Full understanding of flow lines is necessary if an appreciation of their effect is to be attained. Research on the origin and effects of fiber would secure the answer to this problem.

New and better materials are being developed with each passing year. The forging industry must keep abreast of these developments. Research on the new vacuum cast and vacuum melted metals and alloys is necessary to determine their place in the forging industry. This research on forging characteristics should include their advantages and disadvantages over conventional materials as well as economic justification for their use.

Another new technique worthy of mention is the practice of casting small ingot molds and forging directly from the the cast state as done in Germany. This would allow the forger to by-pass the work done by the steel mills and avoid the delays in mill scheduling required for reduction to billet form. Also, the forging manufacturer, without too large an investment, could remelt the scrap resulting from flash (this amount varies between 30-50 per cent on each piece) which otherwise is wasted. This utilization of material would have considerable economical value in lowering the cost of a forging. This method requires research and development to prove that sufficient forging effect and properties can be achieved from the cast state.

The researcher should keep uppermost in his mind the fact that a great number of rejections are caused by defective steel. For the very best forging methods cannot make a good forging from defective steel, while poor forging practice can make poor forgings from steel of excellent quality.

SUMMARY

There are many areas for research in the forging industry. It is a field old in age, but young in development. For too many years, the industry has relied on the merit of its acknowledged superior product. The forging industry has allowed products, with lesser properties, to narrow the gap of superiority through research. If the industry wishes to maintain its present position, the only alternative is renewed and increased progress through research.

Generally, the basic problems have been known for many years. However, due to the empirical nature of drop forging development, little has been accomplished which would lead to fundamental understanding of cause and effect relationships. The attitude of indifference exhibited by forging manufacturers, which accepts such phenomenon as scale formation as a necessary evil is not conducive to continuing progress.

Heating, which has been a part of the industry since its inception, requires much development before it can take its place as a science. Amidst some of the newer equipment, heating furnaces seem to be a product of the middle ages.

Specifically, the areas requiring research in heating are:

1) Development of a test that will determine the effect of overheating and burning.
2) Development of quantitative and qualitative information on the effects of time, temperature, and composition on overheating and burning.
3) Research on scaling and decarburization to establish conditions where these phenomena can be reduced to nonimportance.
4) Investigation on the newer types of rapid heating equipment (induction heating, radiant gas heating, resistance heating) with special attention to the rates of heating and their effect on the material being heated.
5) Study of furnace efficiencies, with and without preheaters, using temperature controls to establish their adaptability for forging furnaces.
6) Study of temperature losses during the forging cycle to minimize the effects of underheating,
7) Development of a method or methods to evaluate the relative importance of each facet of heating.

Concerning die blocks, the following require research:

1) Study of die wear using radioactive tracers or fully activated dies.
2) Establishment of the effect of scale on die life.
3) Effect of die finish on die life.
4) Development of a means for measuring relative extension of die life over the normal die life.
5) Review of the merits of chromium plating and other coatings with special attention to type of die plated and manner and method of plating.
6) Investigation of other methods of surface treatment (ie. nitriding, peening, high heat treatment, etc.).
7) Study of various aspects of lubrication of dies.
8) Methods of completing the finished impressions especially spark erosion and cast die blocks.

In regard to other possibilities for research, the following are important:

1) Research on hydrogen diffusivity and solubility under various conditions and the effect of structure and stress on these properties. This is necessary to designate the exact role of hydrogen in flake formation and embrittlement.

2) Evaluation of a test for forgeability in closed dies.
3) Effect of alloying agents on hot workability.
4) Use of plasticine models for quantitative strain measurements to clarify the effects of speed and mode of deformation.
5) Re-evaluation of lead in forging to promote improved machinability.
6) Study of the origin and effects of flow lines.
7) Investigation of forging from the cast state.
8) Determination of the forging characteristics of vacuum cast and melted alloys plus any of newer metals and alloys.

It is fortunate that many of these remarks do not apply to the entire forging industry. Although a number of larger firms are doing research, there is no free exchange of information in this highly competitive industry.

Much of this research could be accomplished in institutions of higher learning. Other progress will require close cooperation between industry and institutions of higher learning. Problems should be approached from a practical as well as theoretical viewpoint in order that results will have immediate significance. The founding of a drop forging research laboratory, similar to those in Hanover, Germany and Sheffield, England, under the auspices of the Drop Forging Association, would provide a center where common problems of both the small and large forger would be evaluated and solved. A supply of current and past information would allow many of the manufacturers to solve problems without taxing their own organization's time and money.

Hesitation on the part of the forging industry to allot funds for research can lead only to decreased utilization of forged products by future purchasers. An awakening now can avert this dismal future which awaits the drop forging industry.

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