SINTERED MATERIALS ON THE BASE OF IRON WITH SPECIAL REGARD TO ALLOYED SINTERED STEELS

RICHARD KIEFFER & FRIEDRICH BENESOVSKY
Metallwerk Plansee Ges.m.b.H., Reutte, Tyrol, Austria

THE production of 'parts' of all kinds produced of sintered iron, sintered carbon steel or alloyed sintered steel is a kind of mass production which is becoming of increasing importance in industrial countries since the end of World War II[1,2]. In Europe about 3000 tons of sintered parts were produced during 1954 and the production of such parts in the United States is a multiple of the above-mentioned figure. What are the reasons for powder metallurgy to prevail in spite of the highly developed methods of the industries producing or processing iron? Three reasons are of importance:

(1) The utilization of the *porosity* and *plasticity* of sintered iron opened new fields of application not obtained with other procedures.

(2) Sintered material with very valuable *physical* and *chemical properties* can be produced by powder metallurgy.

(3) The cheaper sintering process is used for *technical and economical reasons.*

We shall consider mainly item 3, i.e. the mass production of sintered parts on iron base because of its economical reasons. We shall have special regard to the selection of materials as well as to its development.

Before entering into the details of item (3), there are, however, a few remarks on items (1) and (2).

The utilization of the *porosity* was the first important technical application of sintered iron and bronze parts. A classical example is the *porous self-lubricating bearing* which was considerably applied for technical purposes due to its excellent properties with respect to gliding in normal condition as well as in a case of emergency without lubrication.

A further application of the porosity of the sintered materials is made with *filters*. Such filters, i.e. bronze and stainless steel filters, are applied with diesel and jet engines, cleaning the fuel.

Further applications of porous sintered iron are: *wicks*, *catalysts*, *moulds* and especially *driving bands of shells*.

In the second group comprising materials with special physical and chemical properties, there are a couple of very interesting alloys and auxiliary materials used in the *vacuum technique* as well as for *measuring equipment* and in the *electrical industry*. In this connection we should like to remind you of semi-finished products in the shape of wire and rod of purest iron as well as of iron-nickel, iron-nickel-cobalt, iron-nickel-molybdenum alloys, etc. These materials are used in the industry of incandescent lamps for grids and anodes of radio valves. Making use of the purest starting powders, the sintering process can be done so very clean that the above-mentioned materials are obtained in the purest condition, not gassing again in vacuum. Measuring apparatus and specially the electrical industry need sintered *soft magnetic materials* in the shape of sheets, ribbon, as well as shaped pieces of purest iron, iron-nickel and other alloys. Further, these industries are also in need of *permanent magnets* on the base of aluminium-nickel-iron and aluminium-nickel-iron-cobalt. Productional reasons are taking their part in the manufacture of shaped *permanent magnets* and of *permanent magnetic systems* which are produced by sintering the magnetic materials and the soft iron pole piece together in one single operation.

All these applications of sintered materials on iron base represent mostly special fields in which the sintering technique brought a very valuable enlargement of the available materials or was, in fact, the only one to obtain the desired qualities. Economical reasons are taking their part in the mass production of sintered ready-made parts competitive to the classical methods of mass production like casting, precision casting, die-casting, die forging, stamping sheets, extruding or specially by cutting. Besides, of the special mechanical properties of the sintered materials to be dealt with later, the mostly very clean finish and the high precision of sintered iron and sintered steel parts, the sintering procedure offers a couple of advantages compared with the above-mentioned usual methods, which we can summarize as follows[3]:

Compared with Casting — More exactly true to size, consequently no or only few additional machining of precision parts. Fine-grained structure, easier machining; less time of production, no riser gates, pipes, segregations, no inclusions of foreign material and, therefore, more output.

Compared with Stamping of Sheets — No scrap and, therefore, more output; production in one operation; no intermediate annealing; parts of different wall thicknesses can be produced in one piece.

Compared with Production by Cutting — No scrap and, therefore, no waste of material. The parts are obtained in their final shape and need only very few additional machining; consequently, considerably reduced time of production.

Compared with Combined Constructions — Made of component parts by soldering, welding or riveting, etc. The sintering procedure often allows production of such parts in one piece thus sparing mostly a couple of operations.

The fundamental economical condition of the production of sintered iron and sintered steel parts is a *high number of pieces* provided that there are no other reasons calling specially for this material. The relatively high pressures necessary for the production of dense parts need very precise tools made of best steel, which again for better performance may be carbide-lined. Such dies are, of course, expensive, and if they should make themselves well paid, they have to be used up to almost uselessness. The price of the starting powder is, therefore, of minor importance, though, in this case as well, we have to try hard to make use of cheap but oxide-free and well compressible powders.

Generally speaking, we can say that a powder metallurgical production of 10,000-50,000 parts and more is economical; which is, of course, depending on the nature of the part. The higher the number of parts, the cheaper is a single part, and that is the reason why in many cases powder metallurgical production is cheaper than all other procedures.

The Production of Sintered Iron and Sintered Steel Parts

The production of ready-made or ' tailor made ' parts of sintered iron and sintered steel can be divided, according to Fig. 1, essentially into four different operations[4]. First, the production of the necessary iron powder, its reduction and its sieving in order to obtain the powder ready for compression. The powder or the powder mixture is then compacted to so-called green bodies by means of mechanical or hydraulic presses. The compacts are packed in iron or graphite boats and sintered in reducing atmosphere in continuous furnaces. If very dense parts with a high resistance are wanted, the pre-sintered compacts are re-pressed and re-sintered. Finally, they are coined, oil-impregnated, heat-treated, or get a finish.

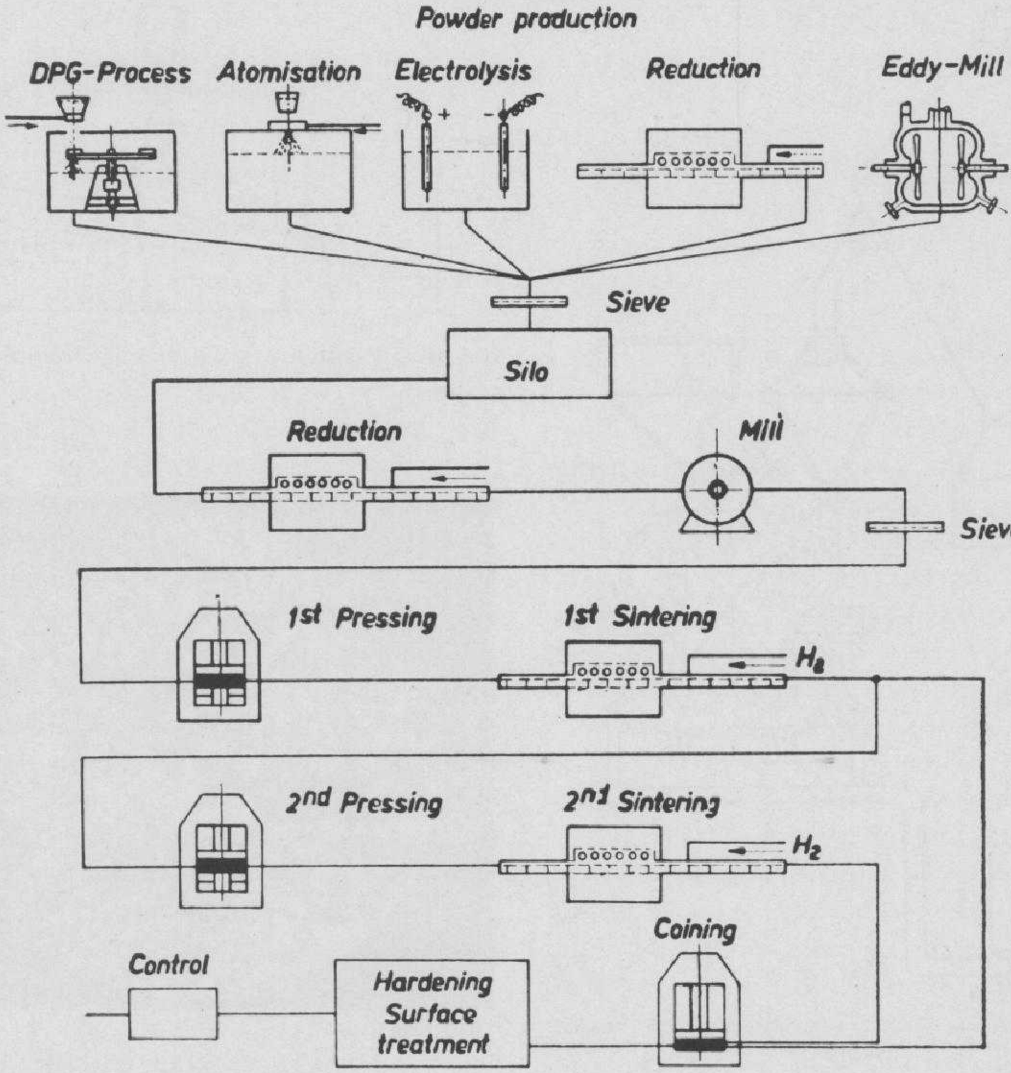

FIG. 1 — PRODUCTION OF SINTERED IRON PARTS

Production of Powder — The powder necessary for the production of sintered iron and sintered steel parts can be produced by various manners[1]. A typical powder as produced by mechanical facilities is the so-called *eddy-mill* or *Hametag powder* made by pulverization of wire pieces, scrap of sheet and granulated metal using an eddy-mill (FIGS. 2 and 3). Atomized powder is, e.g., disc powder (*DPG process*) which is made by smashing a jet of liquid iron by water and by means of a rotating disc (FIGS. 4 and 5). *Pig iron scale powder* (so-called Mannesmann RZ process) is produced by compressed air atomization of pure cast iron of a high carbon content. *Carbonyl iron powder* is made by a physico-chemical process, decomposing gaseous carbonyl of iron. This powder is of globular shape. Swedish *sponge iron powder* (Höganäs process), showing an excellent compressibility, is made by reduction of highly valuable oxidic ores (FIG. 6). The *electrolytic iron powder* (FIG. 7), being very pure and of a good compressibility, is today well introduced in the powder metallurgy of iron. Its use, however, is only economical provided that very cheap electric power is at the disposal for its manufacture.

This abundance of processes for the manufacture of powder seems at first a bit

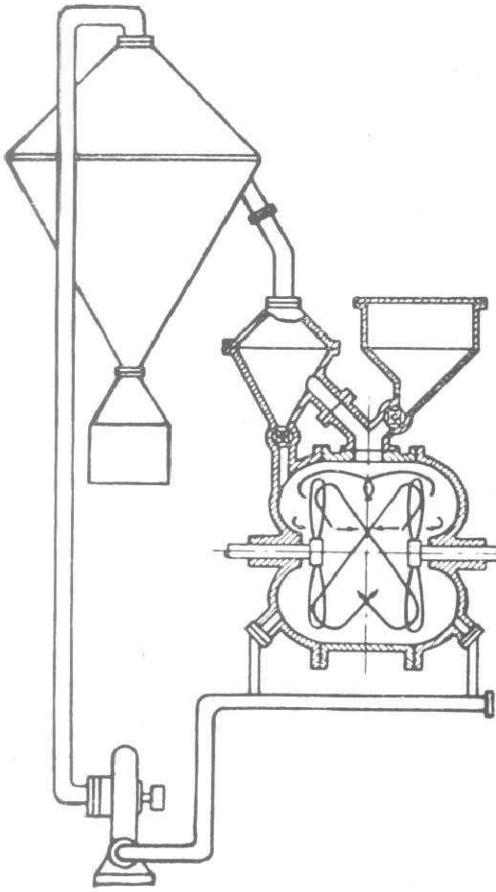

FIG. 2 — EDDY MILL (HAMETAG MILL) SCHEMATIC

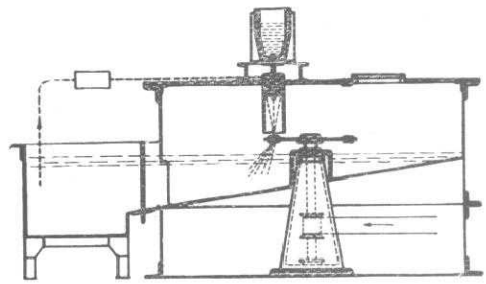

FIG. 4 — PRODUCTION OF IRON POWDER BY LIQUID DISINTEGRATION

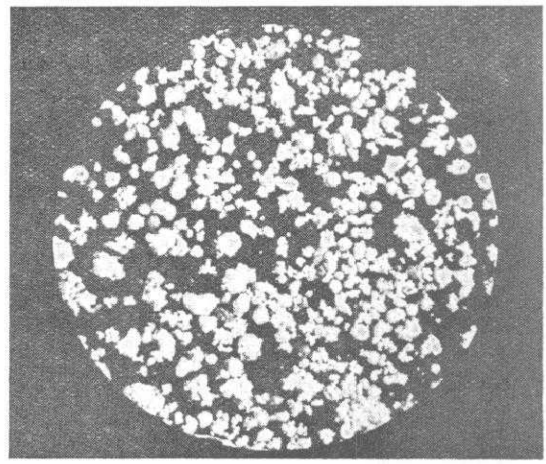

FIG. 5 — ATOMIZED IRON POWDER (DPG PROCESS) × 25

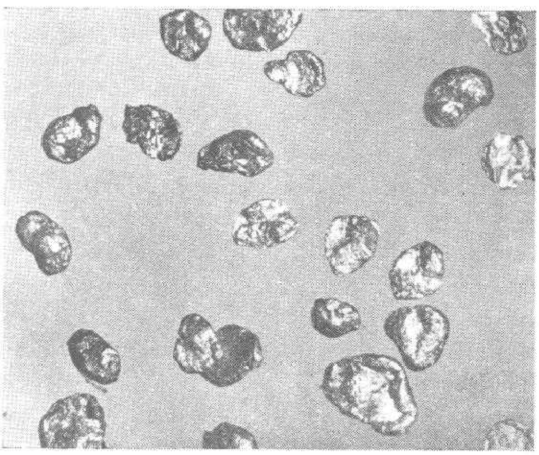

FIG. 3 — EDDY-MILL IRON POWDER (HAMETAG PROCESS). × 25

embarrassing. The development of the powder metallurgy of iron, however, has proved that each one of the various kinds of iron powders finds its application in a certain field depending on its purity, economical production, grain size, grain shape and behaviour. For Al-Ni-Fe sintered magnets and for materials of high vacuum applications, for instance, only carbonyl iron or electrolytic iron powder is taken into consideration because of its high purity, though the price of these powders, at present, is relatively high. The mass production of parts can only make use of cheap powders, simply producible even in greatest lots, the purity of which is of no

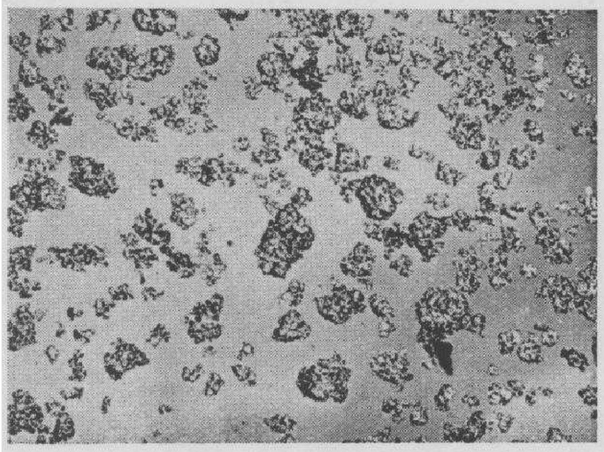

FIG. 6 — SPONGE IRON POWDER. × 25

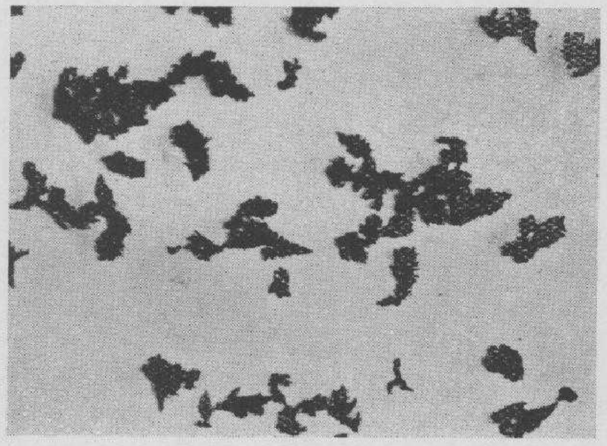

FIG. 7 — ELECTROLYTIC IRON POWDER. × 200

great importance (sponge iron or atomized powders). Besides unalloyed soft iron powders used as starting material for the production of parts of sintered iron or, with some additions of carbon, also for sintered steel, powdered alloys made of simple carbon steels, cast iron, stainless steel and other iron alloys can be produced and processed. Alloyed sintered steels are produced by making use of soft iron powder alloyed with powdered ferrous compounds. The starting powders are very carefully mixed in drum mixers or wing mixers. Irregular starting powders are causing unsteady technological properties of the finished parts.

Compacting — The compacting of the starting powders or powder mixtures is done by means of *mechanical* or *hydraulic presses*, using steel dies which are chromium-plated or carbide-lined in order to reduce wear[5]. Mechanical presses (FIG. 8) like toggle presses, eccentric presses and rotary presses producing simple and small shaped parts will show a high output. Larger and complicated parts involve an exclusive application of hydraulic presses (FIG. 9), as the high specific pressures of about 4 to 8 tons/cm.^{2} (25-50 tons/sq. in.) need high compacting and ejection forces. The size of the available presses is limiting the powder metallurgical process. A 1000 ton press, however, is able to press parts of a surface of about 200 cm.^{2} (31 sq. in.).

The mechanical properties of sintered iron and sintered steel parts are primarily subject

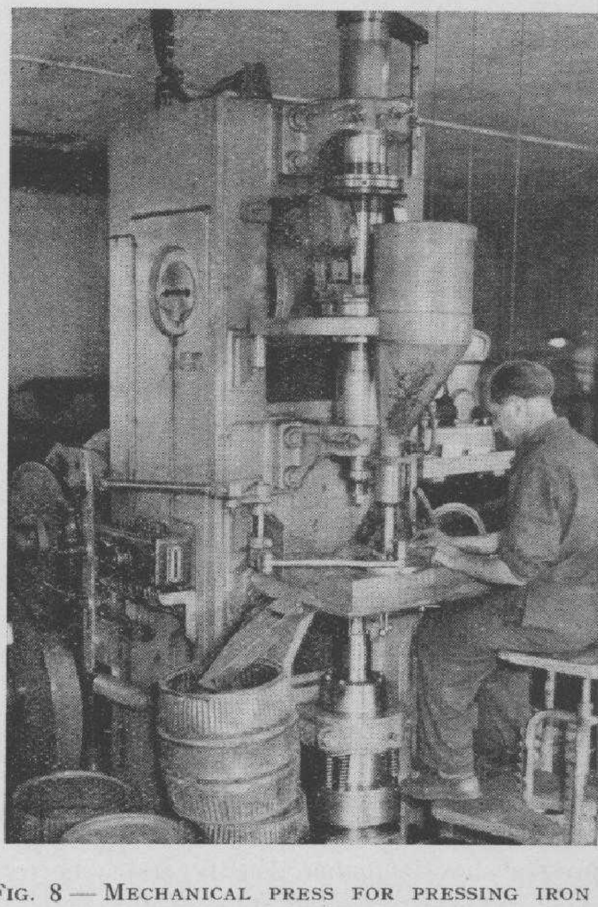

FIG. 8 — MECHANICAL PRESS FOR PRESSING IRON AND STEEL PARTS FROM POWDERS

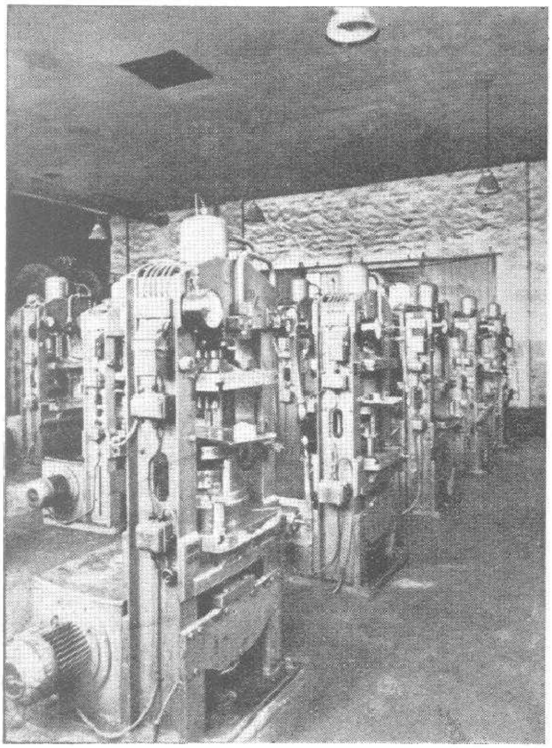

FIG. 9 — HYDRAULIC PRESS

to its density. If we want to produce compacts of the best strength, we have to try to produce compacts of the best density. The density of the green body depends primarily on the applied pressure as well as on the application of the pressure itself (single-action or double-action compacting procedure). Due to economical reasons, the application of compacting pressures of 6-8 tons/cm.[2] maximum (40-50 tons/sq. in.) is recommendable. Higher pressures are desirable but not economical because of the high wear caused by abrasion etc. of the tools.

During compression the iron powder does not flow like synthetic plastic or some ceramic materials and the propagation of the pressure, therefore, takes place only in the direction of the pressure. This explains the fact that parts compacted by single-action presses show a higher density and a better strength of the upside than of the reverse side. Dense parts, therefore, have to be produced by a double-action press, but we have to put up with the effect of a so-called 'neutral' zone of reduced density in the middle of the compact. This is the reason why we cannot produce parts of any height. Parts of graduated shape need tools with divided punches and all of them have to be moved independently and over different spaces.

The compacting of iron powder with its lack of flow would not allow a production of shaped parts having conic, oblique or curved surfaces. If we would produce such parts of uniform density, we would have either to provide complicated and divided punches or to produce a part of a preliminary shape, very often differing heavily from the final one, and to compress this part in a second operation by means of a kind of forging die in order to obtain the desired final shape. Shaped parts subject to high stress must be of a maximum density; the compacting pressure, however, is not to be increased to any value due to the resistance of the tools and the wear involved. The compression and the sintering process, therefore, was successfully divided into several operations. The double-press technique means the production of a pre-compacted part which is pre-sintered, mostly at a low temperature. The final shape is obtained by a second compacting and a final sintering at high temperature. The hot-pressing process, i.e. the application of both temperature and pressure at the same time to the pre-sintered compact, was used because of the same reasons and has proved a certain success. This process has practically been used only sporadically.

Sintering — Compacts of iron and steel powder are today sintered nearly entirely in *continuous furnaces* with *protective atmosphere*[10] (FIG. 10[5]). In the beginning of the iron powder metallurgy bell-type or muffle furnaces were mostly used. Besides the electrically heated continuous furnaces with heating elements of molybdenum, silicon

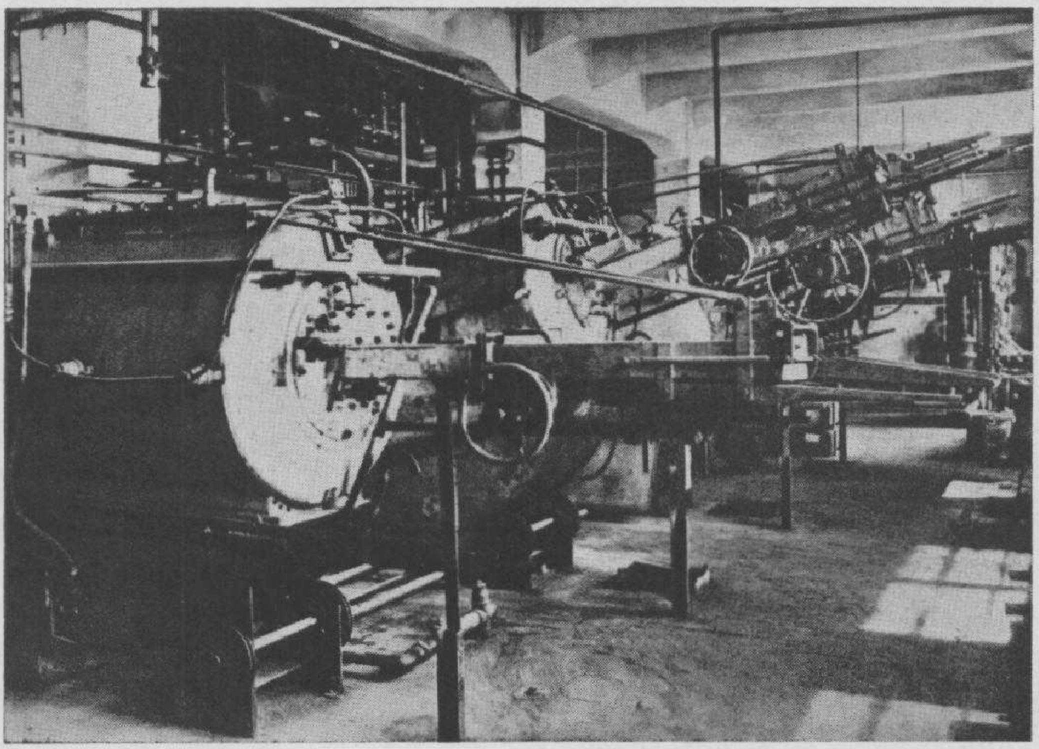

FIG. 10 — SINTERING FURNACES

carbide (Globar) or iron-chromium-aluminium alloys, gas-heated special furnaces were occasionally introduced.

The protective atmosphere consists of purified hydrogen as well as of cracked ammonia, further of partly burnt propane, natural, city gas, or ammonia. During the sintering of steel compacts in hydrogen a considerable decarburization is taking place especially if the starting powder is oxygen-containing and the hydrogen is wet. This effect can be kept well under control by the use of boats of suitable material (graphite). The parts are packed in a suitable ceramic material, mostly Al_2O_3 grit, in order to prevent their contacting the carburizing boats. By so doing we can produce sintered steel parts of a uniform content of carbon.

There are not only metallurgical but also economical reasons which call for a sintering at a temperature as high as possible and over a corresponding short time. Iron parts will be sintered advantageously at 1000°-1200°C. during half an hour. Due to diffusion reasons the sintering time of steel parts is 1-2 hr. at 1150°-1300°C.

The parts are more or less shrinking during the sintering process depending on the original density of the compacts and on the behaviour of the starting powder. The shrinkage in the direction of the pressure is greater than that in the perpendicular to it. For these reasons it is more difficult to keep the prescribed height of the part than its length or width under control.

Subsequent Treatment — In order to guarantee the desired tolerances on the various dimensions of the parts, a *coining operation* of the differently shrunk sintered iron or sintered steel parts is normally applied. This operation is done in steel or better in carbide-lined dies.

An economical *machining* of the sintered iron and specially of the sintered steel parts *by cutting* is only possible by using carbide-tipped tools. The sintered material is short-chipping due to its porosity, a fact which is to be considered when choosing a suitable straight tungsten carbide-cobalt quality as well as the corresponding cutting speed. As to the *thermal treatment* and the *treatment of the surface* of sintered parts, we can say that this is favourably done to a large extent with reference to the processes used for cast iron or steel pieces. Sintered parts of a porosity of less than 10 per cent behave nearly as cast material. A case-hardening of sintered parts by cementing or nitriding shows a quicker and more decisive absorption of carbon or nitrogen because of the characteristic porosity, compared with the cast material.

The well-known *rust-protection methods* like burnishing, phosphatizing with subsequent lacquering, enamelling, electrolytic metal plating, etc., are also applicable to sintered iron and sintered steel parts. The rough and somewhat porous surface guarantees an exceptionally good adhesion of the protective coating.

Sintered Iron

Sintered iron is, as we understand, a material produced of pure iron powder including the usual impurities and containing less than 0·1 per cent of carbon. Table 1 shows the technological properties as a function of the porosity. Materials of a total volume of pores of about 25-30 per cent are used for the already mentioned self-lubricating bearings (FIG. 11). The higher compacted materials or those made according to the double-pressing technique are used for parts subject to smaller stress, e.g. for parts which previously were made of grey cast iron or malleable cast iron. The following parts may serve as examples: lock parts, fittings for buildings, armatures, oil pump gears, roller bearing cages, etc. Fig. 12 shows a selection of sintered iron parts.

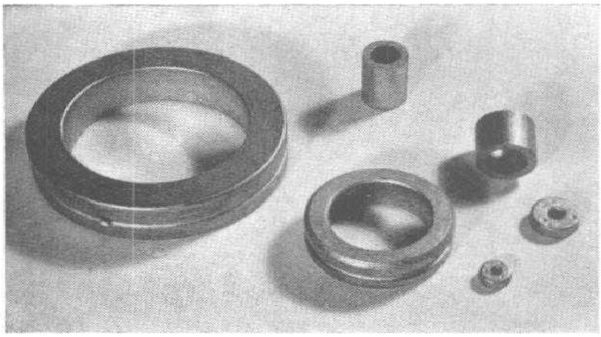

FIG. 11 — POROUS IRON BEARINGS

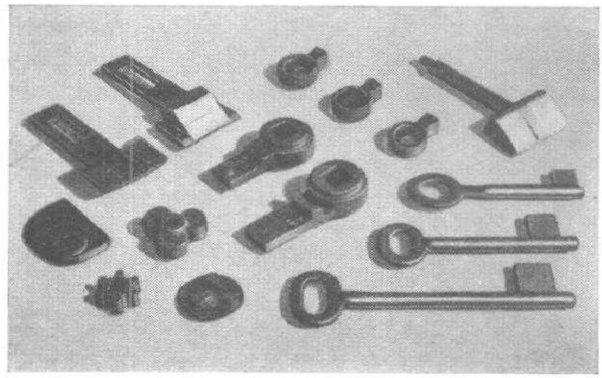

FIG. 12 — SINTERED IRON PARTS

TABLE 1 — PROPERTIES OF SINTERED IRON

COMPACTING PRESSURE, tons/cm.^{2}	DENSITY, g./cm.^{3}	POROSITY, %	HARDNESS H_V kg./mm.^{2}	TENSILE STRENGTH, kg./mm.^{2}	ELONGATION, %	IMPACT STRENGTH, mkg./cm.^{2}
2	5·80	25	30-40	7-10	3-6	0·5-1
4	6·60	15	40-50	14-17	8-10	3-5
6	7·00	10	50-60	19-22	10-15	5-7
8	7·30	6	60-70	22-25	20-25	6-8
6+6	7·40	5	70-80	25-28	25-30	8
Mild steel	7·85	—	80-100	25-30	30-40	8

Sintered Carbon Steel

The strength of sintered iron can essentially be improved by alloying additions of carbon, but the elongation, however, is decreased. The influence of the porosity is, of course, very distinctly noticeable also with sintered carbon steel. As we try in this special field to obtain high strength, we have to produce these parts by applying high pressures or the double-pressing technique. Table 2 shows the mechanical properties of sintered carbon steel parts compared to similar qualities of cast steel. The figures of strength given in this table may serve as a basis for the machining engineer used to such figures of cast materials in designing. We, however, have to emphasize that these figures, valuable for sintered material, are of another meaning, or, in other words, a sintered part showing less favourable figures compared with the cast material is not necessarily worse in this certain case. The entire mechanical properties of sintered materials are dependent on the density. Though the powder metallurgist strives for maximum density of high strength parts, the pressure cannot be raised unlimitedly in practical service (maximum 6-8 tons/cm.^{2} = 40-50 tons/sq. in.) due to the life of the compacting dies. As the metal powder does not easily 'flow' in the die during the compression like plastics or certain ceramic materials, but is only compacted in the direction of the pressure, the compacted green body will show zones of different density. If we, however, want certain criteria of the strength of the material, we can press flat tensile specimens of the very same powder by means of special dies. These specimens are sintered together with the other parts, a method which is similar to the one applied with specimens for testing cast iron. We also can cut tensile specimens out of the finished parts choosing suitable places and examine their tensile strength using special and very precise apparatus (micro-tensile strength tester of Chevenard). This latter procedure has done exceptionally well proving the real properties of the finished part whereas the first procedure results only in some criteria or comparable values. Relating the values of strength to a certain cross-section is only of limited exactness as the effective cross-section is cut down by the alloying constituent 'pores', which is of decisive influence upon the properties.

Similar arguments have to be considered at the examination of the hardness of sintered materials. The various hardness tests are based on the following method: a testing body of a special shape charged by a certain load crushes into a material. The hardness can be concluded from the depth or the width of the imprint. If the material is porous, we receive, especially by application of higher loads, values which are too low and will, moreover, largely scatter. The

TABLE 2 — PROPERTIES OF SINTERED CARBON STEELS

Sintered steel with	Compacting pressure, tons/cm.^{2}	Density, g./cm.^{3}	Hardness H_V kg./mm.^{2}	Tensile strength, kg./mm.^{2}	Elongation, %	Impact strength, mkg./cm.^{2}
0·5% C	6	6·6	110-130	30-35	2-4	1-3
	8	6·9	130-150	35-40	4-6	2-4
	6+6	7·3	160-180	45-50	6-8	3-5
0·9% C	6	6·7	150-170	45-50	2-3	0·5-2
	8	7·0	170-190	50-55	2-4	1-3
	6+6	7·4	200-220	60-65	4-6	2-4

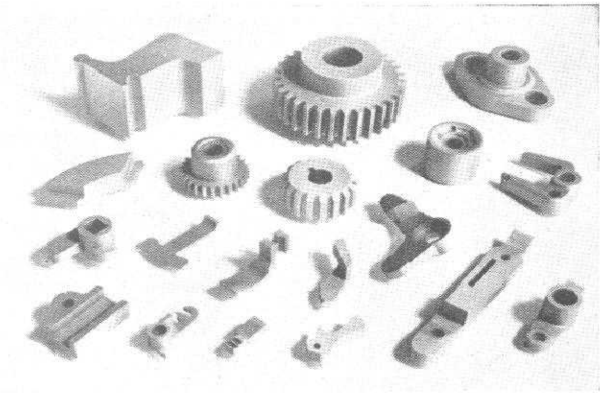

FIG. 13 — SINTERED CARBON STEEL PARTS

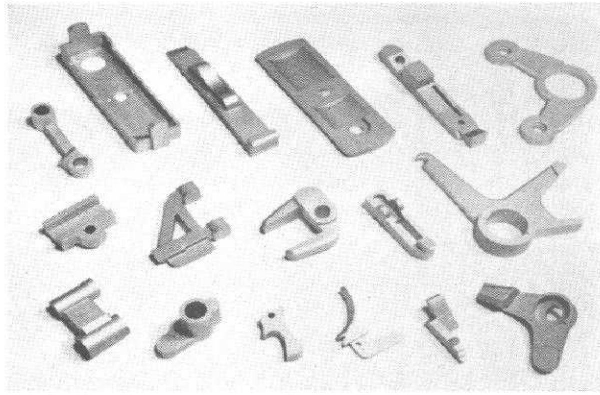

FIG. 14 — SINTERED STEEL PARTS

values as obtained by the usual Rockwell C method — testing-hardened and case-hardened less or more dense sintered steel parts — are too low. If we, however, are testing the hardness of an individual crystal or grain of the steel skeleton by means of a micro hardness tester, we shall find out that the quality of the sintered iron or sintered steel parts is not inferior to cast material. The parts are not at all less suitable. The Vickers hardness testing method with smallest applied test loads has proved to be the best one for the determination of the macro hardness of hardened and also not-hardened sintered materials.

The sintered carbon steel is applicable in many fields and we should like to give the following examples: sewing machines, business machines, bicycles, motorcycles and cars, weapons, textile machines, etc. Figs. 13 and 14 show a selection of a variety of parts produced of sintered carbon steel for the above-mentioned industrial uses.

Alloyed Steel

The development of the iron powder metallurgy and the manufacture of ready-made shaped parts brought very soon a call for materials of specially good case-hardening properties as well as for materials of a good wear and corrosion resistance. We already mentioned that the strength of sintered iron and sintered steel depends on the density and that the porosity can be reduced to a minimum of about 5 per cent only by the application of an economical pressure. It is, therefore, very difficult to exceed certain limited values of strength and elongation of sintered iron and sintered steel and to approach to comparable standards of the cast material. It was very obvious that the sintering technique had to choose the way of *alloying additions* in full analogy to the melting technique, in order to obtain increased strength or special properties like better case-hardening properties, better corrosion resistance, etc. The strength of these alloyed sintered steels is, of course, dependent on the porosity as well. Even if we would apply very high pressures to obtain the highest possible density or make use of the double-pressing procedure, we would have to provide for greatly increased alloying additions compared to the melted material, in order to get similar strength values.

The sintering technique offers a production of alloyed sintered steels containing the additions also used by the melting technique, e.g. nickel, chromium, manganese, copper, silicon, phosphorus, boron, etc. Moreover, it is possible to produce new kinds of alloyed sintered steels by a 'synthesis', alloys which are unknown as a melted material as to their structure and combination. In this connection we should like to mention sintered steels impregnated with copper or copper alloys, sintered steels with additions of carbides, internally oxidized sintered steels, sintered steels of a high boron content in the form of eutectic boron alloys, etc. The scope of this paper does not allow to enter into all of these groups of materials, though partly very interesting, but we would like to pick out only a few groups of alloyed sintered steels the use of which has already practically been made.

Sintered Steel of Copper Content

Contrary to the melted steel where the intentional alloying copper content (1 per cent) is of minor importance (e.g. atmospheric corrosion-resistant and sea water resistant structural steel), sintered copper steel is very interesting for the production of many structural parts of machines and is in use to a large extent[6]. Copper, as an alloying constituent of sintered steel, has several advantages. Its melting point is below that of the usual sintering temperature of iron. During the sintering, it forms a liquid phase, thus effecting an increase in density and promoting the diffusion of the components. The oxides of copper are easily reducible and consequently there are no special requirements to be met with by the controlled atmosphere. Copper powder is relatively easy to produce both in the desired purity and grain size and the price is low compared with the other alloying powders. Further, small additions are of no importance as to the price of the finished product. An addition of copper to the sintered steel means a better strength than pure sintered iron and, provided that the copper has entered into a solid solution, the material can be precipitation-hardened. Further, it is easy to impregnate sintered iron or sintered steel parts with copper or copper alloys, thus forming two-phase metallic materials which can be heat-treated as well.

The iron-copper sintered steel in use today can be divided into three different groups:

(1) Iron-copper alloys with 10-25 per cent copper, produced by infiltration of a skeleton of sintered iron or sintered steel with melted copper or a copper alloy, for instance, Cu-Mn, Cu-Zn. Precipitation-hardening at lower copper contents is applicable.

(2) Iron-copper sintered alloys with 5-10 per cent copper, mostly produced according to the single-pressing technique of a mixture of iron and copper powder. Infiltration technique as well as precipitation-hardening is applicable.

(3) Iron-copper sintered alloys with 0·5-5 per cent copper produced of iron-copper powder mixtures mostly according to the double-pressing technique. Precipitation-hardening usually applied.

An example of a part made of a material of group No. 1 are the compressor *blades of turbo engines* which are produced in America in very large numbers by infiltration of a copper-manganese alloy into a porous sintered iron blade, followed by a subsequent thermal treatment and by a chromium plating[7,8]. Materials of group No. 2 are also largely applied in America. They are of a greatly improved strength compared with sintered iron and are easy to produce at the relatively low sintering temperatures of 1100°-1150°C. The single-pressed alloys of a content of about 10 per cent of copper show a tensile strength of 35-40 kg. per mm.^{2} (50,000-57,000 p.s.i.) and an elongation of 3-5 per cent. A practical application of such a material is illustrated by the millions of shock-absorber pistons already produced (FIG. 15). In order to

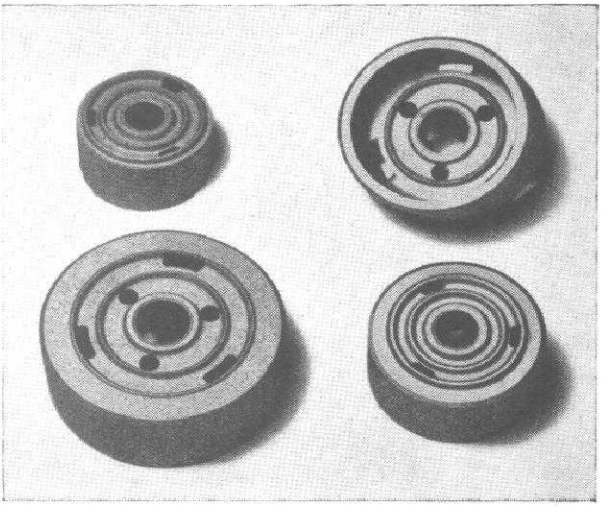

FIG. 15 — SHOCK-ABSORBERS

improve their lubricating properties they are oxidized at about 600°C. by steam after sintering.

The 3rd group of sintered copper steel, however, with low alloying content is of special interest, because we obtain, after a subsequent thermal treatment, a material of high strength and toughness necessary for many structural parts subject to heavy stress. The previously mentioned materials have a two-phase structure showing no more free copper, the copper being completely in *solid solution*.

Before reporting of our own research work we should like first to explain briefly this part of the system iron-copper which is of importance in this connection. The system iron-copper (FIG. 16) resembles very much on the iron edge to the system iron-carbon. This is the preliminary condition of a martensitic (transformation) hardening, and a precipitation hardening is also possible due to the fact that the solubility of copper in iron in the solid state is strongly dependent on temperature (α solid solution at 850°C., 1·4 per cent Cu; γ solid solution at 1083°C., about 8 per cent Cu). A relatively small quenching or cooling speed is necessary for a supercooling of the supersaturated α or γ solid solution respectively. After the annealing, for instance, in the γ field we shall observe an increase in hardness of the sintered copper steel as well as an effect which is in full analogy to the melted materials. In connection with the precipitation effect a very strong rise in hardness and strength together with a corresponding decrease in elongation is produced by annealing the alloy at 400°-500°C.

Fig. 17 shows the details of the change of properties of some sintered copper steels during the heat treatment. These results have been obtained with materials produced as follows:

The starting iron powder was electrolytic iron powder (grain size <0·15 mm.), and an eddy-mill powder (grain size <0·15 mm.). These powders were mixed with 2·5 per cent of copper powder (grain size <0·06 mm.) and compacted to tensile strength specimens by a pressure of 6 tons/cm.^{2} (40 tons/sq. in.). The specimens as produced by the single-pressing technique were put in iron boats and sintered under hydrogen at 1150°C. during 4 hr. in a continuous molybdenum

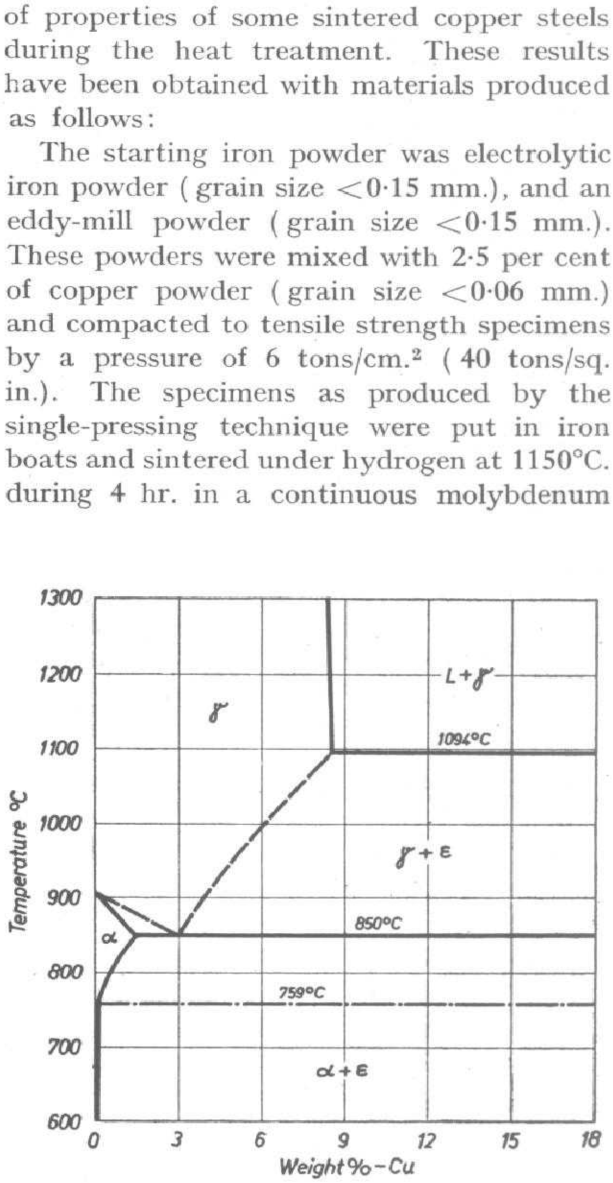

FIG. 16 — Fe-Cu DIAGRAM

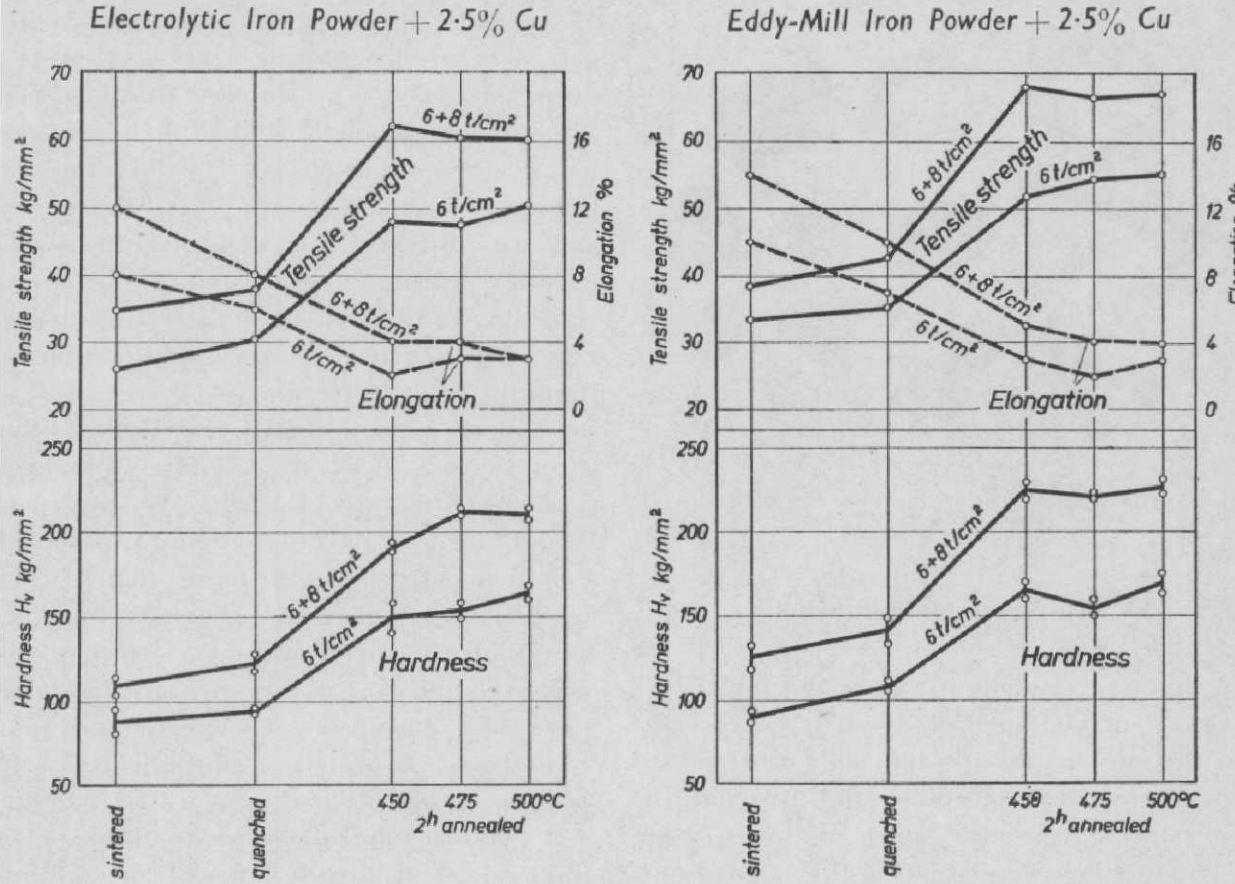

FIG. 17 — PROPERTIES OF SINTERED COPPER STEELS

wound sintering furnace. The specimens as produced by the double-pressing technique were first presintered at 1150°C., subsequently re-pressed by a pressure of 8 tons/cm.² (50 tons/sq. in.) and finally sintered also at 1150°C. for 4 hr.

For precipitation-hardening the specimens were heated for half an hour at 950°C. and then quenched in water, followed by an annealing operation of 2 hr. each at 450°, 475° and 500°C. Fig. 17 shows the change of hardness, strength and elongation, compared to the values obtained with the sintered untreated specimens. Resuming the figures of Fig. 17 we can say that a heat-treated sintered copper steel with a content of 2·5 per cent copper can show the following values: final density, 7·4-7·5 g./cm.³; strength, 65-70 kg./mm.² (92,000-99,000 p.s.i.); elongation, 4-6 per cent; impact strength, 2-4 mkg./cm.² (14-29 ft.-lb.) and Vickers hardness, 210-240 kg./mm.². The above-mentioned sintered copper steel can be case-hardened very well. A precipitation-hardening to obtain a further rise of the hardness is not recommended since the hardness of the case will strongly decrease. The above-mentioned values of hardness are sufficient for a great many structural parts even subject to higher stress. Fig. 18 shows some of these parts, for instance, a chain sprocket of bicycles and light motorcycles, wheel nuts, lock parts, parts of sewing machines, fly weights, etc. All of these parts are made of such a sintered 2·5 per cent copper steel.

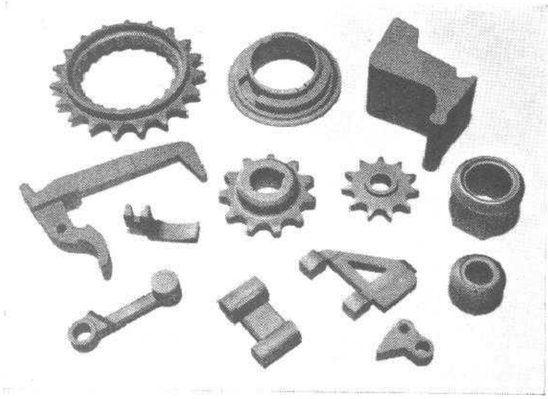

FIG. 18 — SINTERED COPPER STEEL PARTS

Sintered Nickel Steel

Besides chromium, molybdenum, etc., nickel, in contents of about 1-4 per cent, is the most important alloying constituent of structural, heat-treatable and case-hardened steel. Austenitic steel of high nickel content shows special physical and corrosion-resisting properties. Small additions of nickel increase the strength strongly and also the notched-bar impact toughness of the heat-treated material is improved. The great advantage offered by the alloying constituent nickel was the reason for a production of nickel alloyed steel by the sintering technique, favourably supported by the easily reducible nickel oxides as well. Already the first tests in America, however, showed that it was impossible to arrive at homogeneous alloys in spite of the use of finest starting powders, high sintering temperatures, and very long sintering periods because of the slow diffusion rate of nickel. Consequently, there is no economy in the production of sintered nickel steel as yet. We have produced sintered nickel steel containing 0-0·8 per cent carbon according to the double-pressing technique (pressure 6-8 tons/cm.^{2} = 40-50 tons/sq. in.), using eddy-mill powder of a grain size of less than 0·15 mm. and carbonyl nickel powder in amounts of 2-14 per cent[9]. The samples were sintered during 4 hr. at a temperature of 1280°C. (samples without any content of carbon) or 1220°C. (samples with carbon additions). The structure of the steels was homogeneous to a far extent and we observed the usual ferritic, martensitic, pearlitic and austenitic structure according to the content of carbon or nickel. Figs. 19 and 20 give more information of strength and elongation of such sintered steels. The extraordinary increase of the hardness caused by the addition of nickel is very distinct to observe. We, however, should like to add that from a practical standpoint additions of more than 5 per cent Ni are of no great interest. Further, the group of martensitic nickel steel is not applicable due to the very elevated hardness and the difficulties in machining, and, in addition, the sintering time is excessively long for technical conditions.

It was, therefore, obvious to think of an application of already alloyed nickel iron powder as starting material. In America

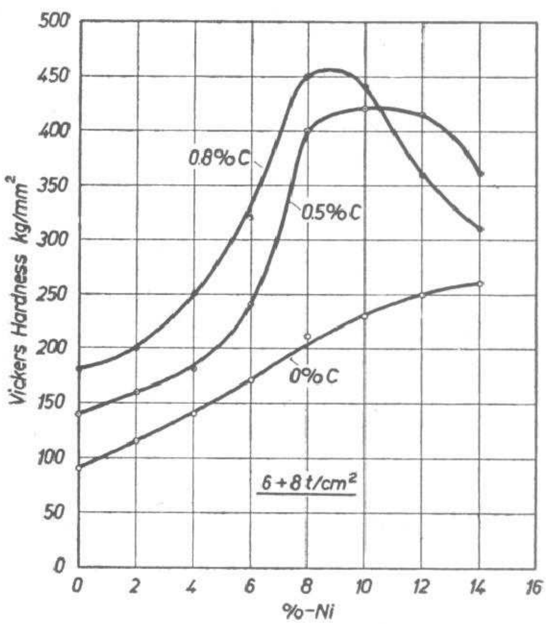

FIG. 19 — HARDNESS OF SINTERED NICKEL STEELS

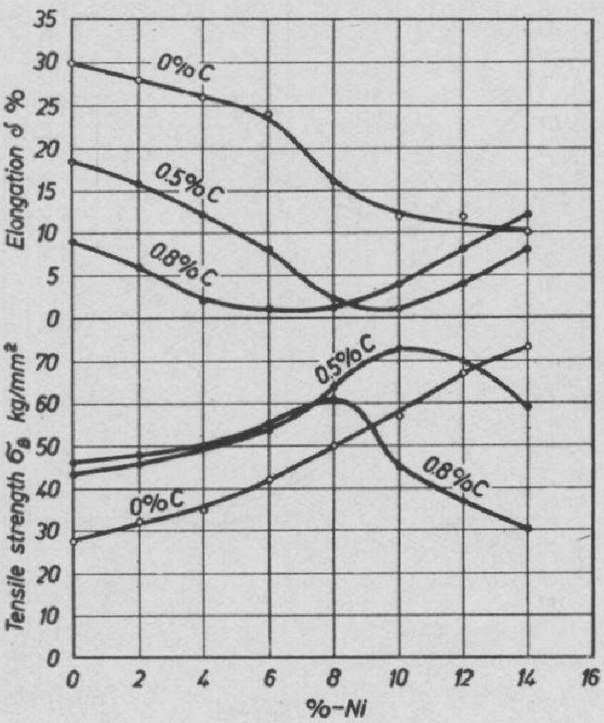

FIG. 20 — TENSILE STRENGTH AND ELONGATION OF SINTERED NICKEL STEELS

the Vanadium Alloyed Steel Co., Latrobe, Pa, is on the market with a powder according to the standard SAE 5650A (Ni, 1·8; Mo, 0·3; Mn, 0·6; Si, 0·2; and C, 0·1-1 per cent) and using this powder, we obtained, in fact, after a sintering time of 2 hr. and a sintering temperature of 1250°C., a nickel steel of a low carbon content showing an excellent toughness.

In order to promote the diffusion and to receive largely dense sintered steels according to the single-pressing technique we tried to introduce the nickel by means of a nickel boride powder. A nickel-boron alloy, containing about 15 per cent boron, melts at as low as 1000°C. and acts as liquid phase during the sintering, thus increasing the density and promoting the diffusion, effects which are well known. The results by our investigations were, in fact, very promising, as we received nickel steel of excellent toughness at a relatively low temperature of 1150°C. and a relatively short sintering time of 1 hr.

Today ready-made parts are in mass production of sintered nickel steels which are hardened either by the usual hardening process or by case-hardening. Similar to the melted materials, nickel is influencing favourably also the sintered material in this sense. We are in a position to obtain satisfactory cases with double-pressed parts by gas-carburizing or case-hardening in solid carburizing agents. The material will be of a hardness of 55-60 RC and of an excellent wear resistance. Such materials are of good toughness in their core and can be used for structural parts of machines subject to heavy stress and heavy wear, for instance, for sewing machines, typewriters and for small vehicles.

Sintered Manganese Steel

There are multiple well-known applications of melted manganese steel. Such steel with a content of 0·1-1 per cent carbon and 0·7-3 per cent manganese is in use as heat-treatable steel for tools of all kinds. The high alloyed steel with 0·9-1·4 per cent carbon and 12-15 per cent manganese is in use in all these cases where high toughness, strength and wear resistance are desirable. The favourable wear resistance of such hard manganese steel is determined by the strong cold deformation during the application. Besides pearlitic and austenitic manganese steels, there is also a group of martensitic manganese steels containing about 0·4 per cent carbon and 5-9 per cent manganese. These steels are practically not machinable and, therefore, never applied.

As manganese shows a relatively quick diffusion rate and its oxide is reducible by hydrogen in presence of iron, we presumed that sintered manganese steels are relatively easy to produce. For our research work we again made use of an eddy-mill powder of a grain size of less than 0·15 mm. and took additions of manganese of 2-16 per cent in the form of 90 per cent ferro-manganese alloy as well as additions of graphite of 0·5-2·0 per cent[10]. The pressure was 6-8 tons/cm.^{2} (40-50 tons/sq. in.) and we sintered at 1200°C. during 3 hr. We found out that these sintering conditions gave largely homogeneous sintered manganese alloys showing ferritic-pearlitic, martensitic and austenitic structures, strictly similar to the melted materials. Figs. 21 and 22 will inform you of the hardness, tensile strength and elongation of such sintered manganese steels with a content of 0·2 and 0·8 per cent carbon respectively. The high hardness and strength of the martensitic manganese steels is striking. We impregnated these steels with copper and found out a maximum Vickers hardness of 750-850 kg./mm.^{2} We think that there may be some practical applications for these very hard martensitic-austenitic sintered manganese steels of top wear resistance if mass production of ready-made parts which need no subsequent machining according to the sintering technique is desirable. Fig. 23 illustrates an example of such a part. It is a spinning ring of a high performance spinning machine.

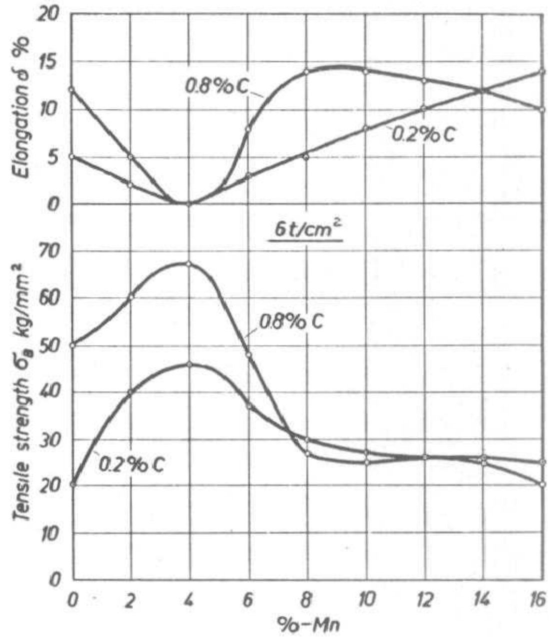

FIG. 22 — TENSILE AND ELONGATION OF SINTERED MANGANESE STEELS

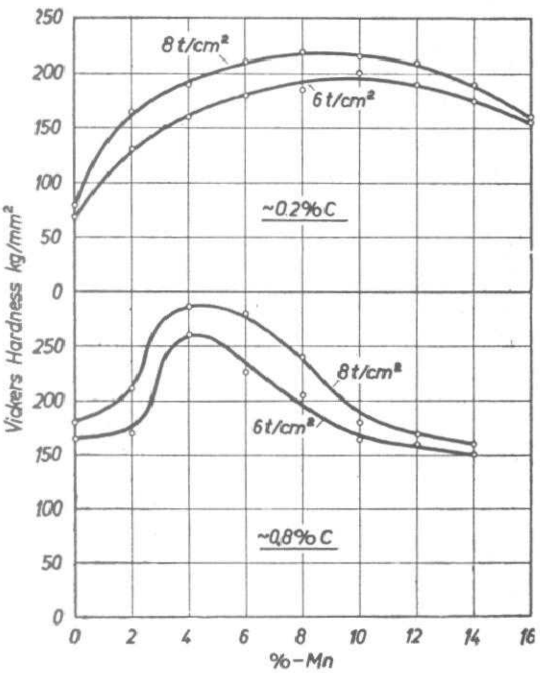

FIG. 21 — HARDNESS OF SINTERED MANGANESE STEELS

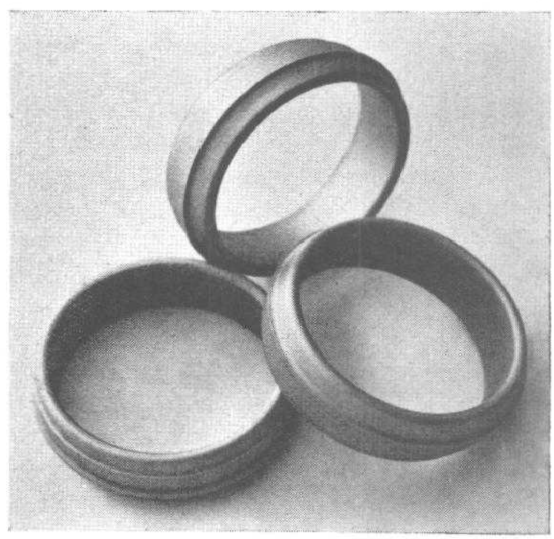

FIG. 23 — SPINNING RINGS

A kind of pulley is gliding with high speed over this ring, and there is no material which could stand this high stress. In return, the relatively porous sintered manganese steel, internally oxidized by a treatment with steam, showed a very good performance. The high hardness and wear resistance of these materials are best illustrated by the fact that such rings cannot be machined in greater lots by the most suitable qualities of cemented hard carbides. If the materials should be machined, this can only be done by grinding.

Chromium-nickel Steel, Stainless Steel

Melted stainless steel is nearly irreplaceable in many technical fields because of the very excellent corrosion resistance. The powder metallurgists, therefore, attempted to produce parts of stainless steel by the sintering process. The sintering technique offered also the advantage of an exclusion of all impurities, specially of the very detrimental carbon. As a rule, we can produce chromium-nickel steels of a mixture of the individual constituents. Chromium and nickel, however, show a very slow diffusion rate and especially chromium forms non-reducible chromium oxide films which inhibit the sintering process. After the introduction of 18-8 chromium-nickel alloy powder produced by intercrystalline corrosion (Wulff process) the sintering in purest hydrogen or in vacuum was successful, thus producing acceptable parts of stainless steel by the application of very high temperatures and a long sintering time. These sintering conditions make the sintered material very expensive, and that was the reason for very small practical production of sintered parts of stainless steel. The material was only applied for special pieces like porous filters, de-icing systems for airplanes, etc. We, therefore, tried to promote the sintering process by the aid of a liquid phase in order to produce also by the single-pressing technique and by economically acceptable sintering times largely dense and homogeneous stainless steel parts[11]. We took an addition consisting of an iron-boron alloy with a content of about 11 per cent boron, forming together with the iron matrix a low melting eutectic phase. In the principle, we also could make use, as already mentioned, of an eutectic alloy of the system nickel-boron. The starting material was formed by two chromium-nickel powders made by intercrystalline corrosion, both being produced by Messrs George Cohen & Sons Ltd., London. The powders were mixed with 2 and 4 per cent of ferro-boron respectively, corresponding to a theoretical content of 0·23 and 0·47 per cent boron. Tensile strength specimens were compacted from these powders by using a uniform pressure of 6 tons/cm.^{2} (40 tons/sq. in.). The specimens were sintered in a vacuum of about 10^{-2} Torr at 1200°C. during 1 hr. The technological data are collected in Table 3. We can see

TABLE 3 — PROPERTIES OF SINTERED 18-8 Cr-Ni STEELS

Composition	Ferro-boron, %	Density, g./cm.^{3}	Hardness H_V kg./mm.^{2}	Tensile strength, kg./mm.^{2}	Elongation, %	Impact strength, mkg./cm.^{2}
18% Cr	0	6·26	75-85	12-13	4-6	1·5
8% Ni	2	7·16	130-150	35-36	8-10	5·0
	4	7·73	260-280	39-41	1-2	1·5
18% Cr	0	6·43	70-80	12-15	2-4	1·0
11% Ni	2	7·26	130-150	35-40	6-8	2·5
2·5% Mo	4	7·66	200-210	35-38	2-4	1·2

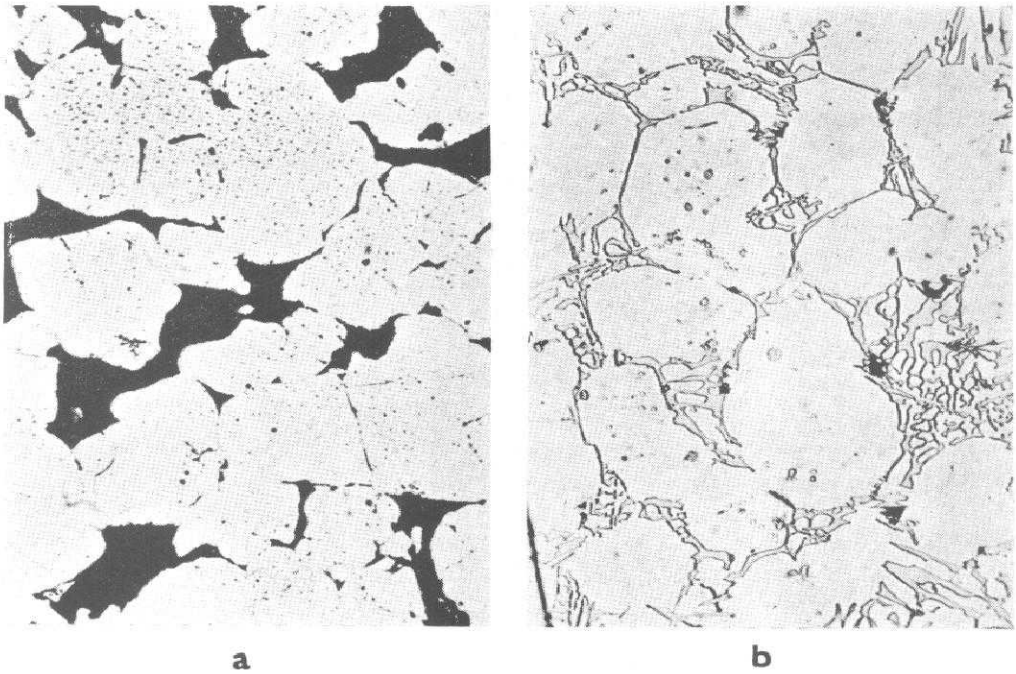

FIG. 24 — SINTERED 18-8 Cr-Ni STAINLESS STEEL: a — WITHOUT FERRO-BORON; b — WITH 4 PER CENT FERRO-BORON

that an addition of ferro-boron is effecting a strong increase in density during the sintering process, mainly based on the liquid boron-containing phase which is promoting de-oxidation and diffusion. Fig. 24 shows this effect very distinctly and you will see the structure of the sintered chromium-nickel steel without ferro-boron (FIG. 24a) and with a content of 4 per cent ferro-boron (FIG. 24b). The first picture shows many pores, the second one shows practically no pores but some remaining eutectical alloy at the grain boundaries.

The sintering of 18-8 steel produced of alloyed powders is very favourably influenced by additions of boron and we receive, even by the use of the single-pressing technique only as well as of relatively low sintering temperatures and short sintering times, very dense materials of a favourable strength. The material of a composition unknown as yet remains to be tested to find out whether the addition of ferro-boron is not detrimental to its corrosion resistance. If this is not the case, a large field of applications is opened for this material because of its economical production.

Summary and Prospects

The production of sintered iron and sintered steel parts, as shortly described, is a valuable completion of the present mass production methods in use for structural parts of all kinds. Such parts are mainly used in great numbers by the small machine industry for cycles, motorcycles and cars, for locks and fittings, for weapons and for many other applications. We discussed briefly the properties of sintered iron of various density as well as of carbon steel, produced either by the single-pressing or double-pressing technique. Parts subject to higher stress require alloyed sintered steel of increased strength and toughness. Sintered copper, nickel and manganese-containing steels are suitable for these purposes and we discussed their manufacture, properties and applications. Even corrosion-resistant parts made of alloyed 18-8 chromium-nickel powder can be sintered. Additions of ferro-boron have proved to influence favourably the density and to promote the diffusion during the sintering process.

Very favourable future applications will be opened not only for the above-mentioned alloyed steels but also for sintered materials impregnated with copper or copper alloys provided that the production cost can be cut down by the production of a high number of pieces as well as by a simplification of the method of production itself.

References

1. KIEFFER, R. & HOTOP, W., The field of iron powder metallurgy is in detail described in the monograph "Sintereisen und Sinterstahl" (Springer Verlag Wien), 1948.
2. KIEFFER, R., BENESOVSKY, F. & BARTELS, H. J., *Industrie und Technik*, **2** (1947), 64-66, 88-92; *Powder Met. Bull.*, **2** (1947), 54-69.
3. BENESOVSKY, F., *Werkstatt und Betrieb*, **83** (1950), 257-260.
4. BENESOVSKY, F., "Einführung in die Pulvermetallurgie", *Graz* (1948), 84-101.
5. KRALL, F., "Einführung in die Pulvermetallurgie", *Graz* (1948), 55-83.
6. ZAPF, G., *Stahl und Eisen*, **74** (1954), 338-347.
7. KIEFFER, R. & BENESOVSKY, F., *Berg-u. Hüttenmänn. Mh.*, **94** (1949), 284-294.
8. STERN, G. & GERZINA, J. A., *Iron Age*, **165**(8) (1950), 74-77.
9. BENESOVSKY, F., *Berg-u. Hüttenmänn. Mh.*, **96** (1951), 184-187.
10. BENESOVSKY, F. & KIEFFER, R., *Berg-u. Hüttenmänn. Mh.*, **95** (1950), 145-150.
11. BENESOVSKY, F., HOTOP, W. & FREHN, F., *Planseeberichte*, **3** (1955), 57-70.

#

#

#