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ON TITANIUM

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PROCEEDINGS
OF THE
TITANIUM SYMPOSIUM
AT

WATERTOWN ARSENAL, WATERTOWN, MASSACHUSETTS

8 OCTOBER 1952

WATERTOWN ARSENAL
WATERTOWN, MASS.

METALLURGICAL ADVISORY COMMITTEE ON TITANIUM

Information Bulletin No. 75

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FOREWORD

In accordance with the desire to make available pertinent information to the Titanium Program there is given herewith the full proceedings of the Titanium Symposium held at the Watertown Arsenal on 8 October 1952. The symposium was held under the joint sponsorship of the Associated Industries of Massachusetts, the American Ordnance Association, the Watertown Arsenal, and several manufacturing and metal trade associations of New England.

The symposium was devoted to a practical discussion of the properties, processing, machineability, and similar characteristics of titanium. This metal is being developed as a strategic Ordnance material because of its lightness, combined with its high strength. Attention was focused on the phases of the new metal that would be most helpful to industry and commercial fields as well as to Ordnance.

The symposium was under the direction of Colonel B. S. Mesick, Commanding Officer of Watertown Arsenal and Coordinator of the Army Titanium Program. The coordination with industry, needed to present the symposium, was arranged through Mr. Ralph S. Towne, Small Business Specialist at the Watertown Arsenal.

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TITANIUM SYMPOSIUM PROCEEDINGS

EDITOR'S NOTE: To facilitate presentation introductory comments have been omitted.

INTRODUCTION

Greetings were extended by Mr. F. Gorham Brigham, Jr., Chairman of the Titanium Symposium, President of the Boston Branch of the National Metal Trades Association, and Assistant Treasurer and Secretary of the Saco Lowell Shops. Col. B. S. Mesick, Coordinator, Army Titanium Program, and Commanding Officer of the Watertown Arsenal welcomed those in attendance and invited them to inspect the exhibits.

TITANIUM COMES OF AGE

By: **LT. COL. THURSTON T. PAUL**, Director, Research, Development & Engineering, Watertown Arsenal

Much of the information on the "wonder metal" titanium has been published in highly technical and abstract reports not suited for the needs of fabricators and retailers. Of those reports which have been prepared for nontechnical consumption, some have been over-optimistic, some over-pessimistic, and some misleading. For the past several years, Watertown Arsenal has been the Army's center of research and development of this new metal. With this background, today we will give you the facts, presented by a number of distinguished gentlemen with first-hand experience in those fields of titanium fabrication which are of greatest interest to you.

The little story that I will tell you of titanium's development, all started several billion years ago, and the first hand of influence was that Creative Power which formed our planet. For ages following, mankind was much too interested in maintaining the principal elements of life to bother about titanium, or even to know that such a material existed as Element No. 22 in the periodic table.

In 1791, we find our first recorded knowledge of the existence of titanium. In that year, an English clergyman and amateur chemist, William Gregor, noticed that the black sands of Cornwall were half white, and determined that this white stuff was a metallic oxide which we now know was titanium oxide. Thus we see that our meeting here today is a direct outgrowth of Gregor's rather singular ability to tell white from black.

Our billion-year old infant developed ever so slowly. A few years after Gregor published his work, an Austrian named Klaproth succeeded in extracting the metal from the titanium oxide ore rutile. Because of the strong bond this metal showed for oxygen and other impurities, he named the new metal "titanium," after the Greek god renowned for his enormous strength.

Relatively pure titanium was not isolated until 1835. Confined entirely to small laboratory experiments which were necessarily slow and arduous, our baby's infancy extended over another hundred years or so. New laboratory methods for reducing various titanium compounds were developed, but the metal so strongly bonded to other elements proved to be a completely uncooperative subject. Its reluctance to part from its chemically associated buddies, principally oxygen, was evident from the very first attempts at reduction. That same reluctance persists today as a stubbornness in the growing child which has not been lessened in spite of concerted efforts of all its foster parents.

The basic reduction process which is now in use was developed in 1932 by Dr. Wilhelm Kroll, climaxing years of experiments in Luxemburg, Germany, and the United States, the latter as a consultant to the United States Bureau of Mines. In 1946 the Bureau published its Bulletin No. 7381, "Metallurgy of Titanium and Its Alloys," the first major report published on our child. In that same year, the Bureau established a pilot plant using the Kroll method of reducing titanium tetrachloride with pure magnesium. Its success in producing 100 pound batches of titanium sponge launched the titanium industry of today, and our child became an adolescent, with all the attendant trials and tribulations of growing up.

Let's look at what we've nurtured. Titanium is a light, strong, corrosion-resistant, and ductile metal. To these characteristics we can add one more very important qualification: It is plentiful. It is the fourth most abundant structural metal in the earth's crust, exceeded only by aluminum, iron, and magnesium. Its principal ores are rutile (TiO_2) and ilmenite ($FeTiO_3$), and are found extensively throughout the United States, Canada, India, Australia, Norway, Ceylon, Brazil, Sweden, and the USSR. Both rutile and ilmenite are found in the beach sands at many places along our Atlantic, Pacific, and Gulf coasts. Other known titanium ore deposits occur in Virginia, North and South Carolina, New York, Minnesota, Rhode Island, Wyoming, California, New Mexico, Tennessee, New Jersey, Colorado, Montana, Oklahoma, and Arkansas. Our Bureau of Mines estimates that in the world's largest titanium ore deposit at Allard Lake in eastern Quebec there are at least 300 million tons of ilmenite, and that more than 50 million tons of titanium metal can be produced from that deposit alone. At 5000 tons per year, this one deposit alone will furnish us titanium for 10,000 years!

We can be assured that known deposits of titanium-bearing ore will amply supply industry far into the foreseeable future. In the event of an all-out war, the United States would not be dependent on any outside nation for its titanium ore. And even at the present low rate of production, titanium ore is not expensive, ranging from 2 to 6 cents per pound. So our youngster's future seems secure enough. Now let's get back to his good and bad qualities.

He has the build and physique to develop into a middleweight champion. Titanium and its alloys have an outstanding strength-to-weight ratio. When substituted for steel, titanium can result in up to 40% saving in weight for equal strength.

Titanium has shown corrosion resistance equal to or better than stainless steel for most applications. It compares with platinum in its ability to withstand salt water corrosion.

Titanium is stiffer than either aluminum or magnesium. Its modulus of elasticity is in the order of 15 million, roughly half that of steel, but more than its other competitors.

At temperatures between 300° and 800°F, titanium does not lose its strength or soften as do aluminum and magnesium, and it is in applications involving such operating temperatures that titanium is expected to find its most widespread use initially.

These statements make our youth seem to be a fair haired boy, but he has an alter ego, too. At times, he's just plain ornery to handle.

If held at temperatures above 900°F for any extended time, titanium absorbs nitrogen and oxygen from the atmosphere and becomes brittle and useless.

Compared with stainless steel, titanium has shown very poor ability to absorb sudden forceful shocks without breaking. Experimental alloys have shown, however, that the impact strength can be increased remarkably by controlling impurities and alloying.

The liquid metal seems to be a universal solvent and either dissolves or is contaminated by every known refractory.

We have heard reports that the machining and fabrication of titanium is not as readily accomplished as steel. Our program today will more closely examine this problem and will bring you the latest experiences of several of our leading authorities.

These are his moral and physical weaknesses. Just as with the human child, parental attention to these defects and careful training can overcome or minimize these weaknesses and permit the growing boy to reach his full stature and usefulness.

Fundamental work in alloying titanium started about 1947, and currently is the subject of much investigation by producers of the metal and by large Government research programs. The most commercially promising alloying elements investigated so far include: aluminum, manganese, chromium, iron, vanadium, tungsten, molybdenum, carbon, oxygen, and nitrogen. The majority of alloys developed so far have been

general purpose alloys of higher strength than commercially pure titanium alloys which will compete with aluminum on a strength-to-weight basis at room temperature.

The titanium development program has been accelerated largely through interest and subsidy by this country's Armed Forces. This effort has resulted in expanding production of raw titanium from a total of 2 tons in 1947 to 500 tons in 1951. An output of 1400 tons is expected this year, and it will increase to at least 3500 tons in 1953. The cost per pound of wrought titanium in 1948 was \$100.00. At present, basic prices range from \$6.00 to \$10.00 per pound for forgings, bar, and rod, to \$15.00 to \$20.00 per pound for sheet and strip. If a less complicated and continuous production type of process can be developed for reducing titanium ore, prices will fall sharply and usage will boom accordingly.

While the interest in titanium was initially spurred by a military demand, the metal's strength, lightness, and resistance to corrosion are qualities not to be overlooked for peacetime applications. Many commercial uses will be found as the metal becomes more widely known and available to designers, engineers, and manufacturers. It is certain that in the future metals markets, titanium will typically be the aggressor, seeking to displace its competitors in usefulness and to become a competitor in price.

And so our billion-year-old infant comes of age. To be sure, he's still a callow youth, but in the last five years of his development he has shown himself to have those qualities we most need in a middle-weight champion. His development to fulfill his capabilities, gentlemen, rests with his foster parents - researchers, producers, fabricators, designers - you.

INDUSTRIAL FUTURE OF TITANIUM

By: COL. B. S. MESICK, Coordinator, Army Titanium Program and
Commanding Officer of the Watertown Arsenal

Colonel Paul has indicated the current production and the anticipated production for the calendar year 1953. As the result of that increased production there will naturally be a reduction or lowering of price as has already taken place since 1948. It is well known that an increased demand for a product results in an increased production followed by a further reduction in price. Therefore, it is hoped that the Symposium presentations will ultimately result in adding the civilian or commercial demand to the military demand for titanium.

Since many of the subjects to be presented are concerned with the fabrication of wrought material, it is appropriate to review briefly the

steps of production from the ore to finished commercial product. Ore is reduced to metallic titanium by a magnesium reduction process - the so-called Kroll process. I prefer to call it the magnesium reduction process because titanium is produced first by forming titanium tetrachloride and then, by introducing magnesium to the titanium tetrachloride, removing the chlorine from the titanium leaving a spongy metallic titanium. This spongy metallic titanium is contaminated with a certain amount of magnesium chloride which can be distilled off from the mass leaving very pure titanium sponge.

There are many new processes being worked on by various industrial companies. Most are still in the laboratory stage. A few are in the pilot plant stage, but all of you know that it takes from 18 to 30 months to build a plant, so we must stimulate the demand and consumption of titanium produced by the present magnesium reduction process.

The melting of the titanium sponge is being done in the type of furnaces which have been used for a long time in the steel industry. In general we have two types, arc melting furnaces and induction melting furnaces. Because of the high melting point of titanium, graphite is the standard crucible material used in induction furnaces since they have to be made to stand-up under high temperatures. The resulting alloy or commercial grade titanium made by this method may be high in carbon. We have found with titanium alloy, the same as we did in steel, that we must keep the carbon down. Therefore, most of the production today of wrought material is being melted in arc type furnaces and is cast in the form of ingots.

Some of the new processes may enable titanium to be melted and poured directly into the form of a pig or billet. The present standard practice is to slowly build up the metal as a cylindrical ingot. Before the end of the year one of the producers will be producing two-ton ingots.

Titanium ingots are forged, rolled and drawn into finished products in the same manner as steel. The commercially pure titanium is put through the same wire drawing dies as those used for the steel industry, but we have had a great deal of trouble in drawing alloy titanium.

Based on the titanium development work conducted over the last 2 years, two specifications have been adopted and approved by the Department of the Army. The sponge titanium is MIL-T-12118(ORD), 15 July 1952, and the specification for wrought material which covers most of the standard forms of wrought material is specification MIL-T-12117(ORD), 15 July 1952. To obtain copies of these specifications address the Commanding Officer, Watertown Arsenal, Watertown 72, Massachusetts.

Based on these specifications you will find that practically all of the military uses require alloy because of the high strength density requirement, and particularly the high impact value. Where high impact

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value is required we use very high quality sponge. The standard commercial grades of titanium have highly satisfactory physical properties for most commercial uses, particularly where high impact properties are not required. Titanium is not under allocation, you merely deal with the regular vendors.

AVAILABILITY OF TITANIUM

I

By: T. W. LIPPERT, General Manager of the Titanium Metals Corporation of America, New York, New York

The extraordinary corrosion resistance and lightness of titanium will undoubtedly assure it a very prominent place among engineering metals. The most common grade of titanium is commercially pure titanium. No alloy elements are deliberately added. It is the best possible material that can be made at reasonable costs. That material is on the order of 90,000 psi tensile, as annealed. It would compare a little bit above the usual grades of stainless steel. If you have ever handled stainless steel, and have the skill necessary for handling that metal you can easily handle commercially pure titanium.

When we come to titanium alloys you face a entirely different situation. Most manufacturers jump from commercially pure titanium to alloys in the area of 150,000 psi tensile, as annealed. Those materials are available in forging stock and in sheet metal. The material does not form too easily. It is rather difficult to machine from its hardness and strength. It is impossible yet to fusion weld such alloys. Spot welds are only normally good, however, not good enough to be considered a standard for manufacturing procedure. Most such alloys today are used in forged parts or riveted structures.

The industry as a whole in 1953 will probably produce titanium in quantity, and if sold at present market prices would probably total some one hundred fifty million dollars. Much of the money for the purchase of this material comes from military sources. The total purpose of the military is to build up an industry, to drive down price, to expand civilian production, and therefore, have a civilian base to draw from in times of necessity. I rather think that prices will drop next year as production goes up.

AVAILABILITY OF TITANIUM

II

By: W. C. BECK, Sales Engineer of the Mallory-Sharon Titanium Corporation, Niles, Ohio

The Mallory-Sharon Titanium Corporation manufactures arc and induction melted material. Flat rolled products up to 44 inches in width - bars, slabs, strips, and sheet plates can be produced along with forged sections, rods, rounds, extrusions, et cetera. At present a limiting size factor is a maximum ingot of 1000 pounds, but with improved methods of melting, and larger diameter crucibles, we hope to increase this size.

One of the outstanding advantages of titanium is its good weight-strength ratio. It is about 60% heavier than aluminum, but only about 56% as heavy as special alloyed steels. Many of our problems as producers hinge on solving the technological problems by learning how to melt, to maintain good strength level, good percentage of elongation, improve impact properties and things of that nature.

Good mechanical properties in the intermediate range of 400° to 800°F, place titanium in an ideal position. At temperatures about 800° or 900°F, titanium loses strength and becomes embrittled. However, it has been used, and used successfully, for short periods of time at temperatures around 2000°F, but understand, this is just for short time applications.

Titanium possesses very good corrosive-resistant properties. Its immunity to salt water corrosion, and marine atmospheres is very important to many applications.

We are melting titanium by two methods: (1) the induction type, and (2) the arc type. Both methods melt from the sponge to the ingot stage and are carried out under an inert atmosphere - the induction melting being done in a graphite crucible, and the arc melting being done in a water cooled copper crucible. Induction melting is the simpler type by merely melting sponge material in a graphite crucible and pouring the molten metal into a graphite mold. However, it is recognized that the absorption of carbon is detrimental. Carbides resulting cause difficulty in machining and welding, and also to a slight extent lower the elongation properties. We have found that it has not affected our heat treat, but it has affected the elongation to a certain extent. This induction type melting does give a more homogeneous ingot, and consistency from heat to heat is a little more predictable. Induction melting at the present time seems to offer one of the best avenues for utilizing scrap.

Melting in a water cooled copper crucible is the arc method of melting employed. We are using carbon electrodes. Contamination is much less of a problem using this type melting, and with improved furnace designs, many of the difficulties now encountered should be overcome. The ingots can be built up individually, or extracted continuously. The ingot itself, once removed from the mold is handled very similarly to steel. It is scalped to remove the outer layer or laps which might have resulted from the melting. At the present time work to successfully extrude shapes and tube sections is under way, and probably the method we are employing now is a little bit different than is currently being used, but the initial results look very promising.

Commercially pure arc melted titanium is sold under the trade name of MST Grade III material. Physical properties for hot worked, annealed material run in the range: yield strength - 60/85,000 psi, tensile strength - 85/100,000 psi, and with 15% to 20% elongation. This form is most suitable where very high strength is not essential, but where the material must lend itself to good forming and good welding properties.

An example of a very high strength alloy we are currently producing is MST Grade: 3 Al.-5 Cr. material, which has a yield strength of 140/160,000 psi. Elongations naturally are much lower in this type of material; around 6% to 12%.

AVAILABILITY OF TITANIUM

III

By: THOMAS E. PERRY, Metallurgist, Republic Steel Corporation,
Massillon, Ohio

We have been melting titanium ingots for approximately 2 years. It is only within the past 6 months that we have felt that the technology melting and processing of titanium in our plants has reached the point where we felt that we could put it on the open market.

Generally speaking, the induction melted product, as compared with the arc melted titanium is slightly less ductile, is more difficult to machine, and in general has lower impact strength, and due to the high carbon, which may run between 40 and 100 points, is not considered a weldable grade of titanium. Its advantages are simply that the product is uniformly reproducible, and the ingot is homogeneous. The entire charge is molten at one time and the diffusion throughout the ingot gives excellent chemical uniformity in the finished product.

The induction melted product is extremely important in that by induction melting we can utilize the scrap generated in the mill, and from

the mill's standpoint the price of titanium by either process will be considerably reduced. From the induction melted product, in the alloyed form, we can obtain tensile strengths up to about 200,000 psi, ductility in the range of 4 to 8 or 10% and for many applications, such as high strength forgings, where ductility and impact are not of primary concern, the induction melted product is the logical choice.

As far as arc melted titanium is concerned you can buy today three commercially pure grades of titanium. The three grades are determined by essentially the impurity level when the commercially pure product is melted. There is a high ductility commercially pure titanium which has yield strengths between 40,000 and 45,000 psi, in which the ductility range is up close to 30%. There is an intermediate range in which the yield properties run between 55,000 and 70,000 psi. The ductility is measured by elongation and runs about 25%. The higher strength commercially pure titanium which has a minimum yield strength of 70,000 psi, has elongation to the order of 22% or 23%. You can buy alloy grades of titanium at yield strength levels of 110,000 and 120,000 psi minimum. We have seen tensile strengths of the order of 200,000 psi, with elongations close to 20%. Those, however, are not commercial applications.

For the most part today much of the alloyed titanium on the market, and a good deal of the fabrication of alloyed titanium, is still in the evaluation and reproducibility stages. The only way the material can come out of that stage is by continued use over an extended period of time. This, we hope, will be the course, as the various products come out of the developmental stage, as potential consumers use the products that are available now, and help in evaluating not only the materials, but also the techniques used in fabricating.

AVAILABILITY OF TITANIUM

IV

By: G. T. FRASER, Sales Manager, Rem-Cru Titanium, Incorporated,
Midland, Pennsylvania

Many of you are interested in becoming acquainted with titanium, and to evaluate its possible use in your particular field. Our research and development groups are most interested in cooperating with any titanium users in evaluating new applications for this metal.

We produce two grades of commercially pure titanium, RC-55 and RC-70. These two grades are designated by the numbers 55 and 70 to denote the minimum yield strength. The RC-55 grade has a minimum yield strength of 55,000 psi, and the RC-70 a minimum yield strength of 70,000 psi. We are currently producing, on a production basis, two titanium base alloy

grades, RC-130-A, and RC-130-B. Grade RC-130-A is primarily an alloy sheet material having 7% manganese with a minimum yield strength of 110,000 psi. Our RC-130-B is a titanium base alloy containing 4% manganese and 4% aluminum, with an average nominal minimum yield strength of 130,000 psi. This particular grade is primarily a bar and forging alloy. It is not considered as a sheet alloy.

Our commercially pure titanium grades are furnished in all standard forms, such as: sheet, plate, wire, bar, tubing, forgings and billets. The minimum gauge of sheet which we furnish in the commercially pure grade is .016". Our standard size sheet is 36" x 96". However, we are producing sheets 48" x 148". The titanium base alloy sheet, RC-130-A is produced in a minimum gauge of .025". It is available in standard size sheets 36" x 96". The alloy material which is used for bars and forging alloys, RC-130-B as well as RC-70 is produced in all standard sizes of bar, square, rectangle or round, and also in billets up to approximately 1,000 pounds in weight. Tubing at the present time is furnished in the RC-55 commercially pure grade. Tubing sizes will vary from 1/8" O.D. up to approximately 3". The maximum wall thickness is 1/8" at the present time.

The fact that titanium is available today in most standard forms does not necessarily mean that it is available in unlimited quantities. It is estimated that 1500 ingot tons will be produced this year by the entire titanium industry, and we are hopeful of reaching at least 4,000 ingot tons during the year 1953. Such a production figure is based on the estimated quantity of titanium sponge that is going to be produced during 1953.

To those of you who feel that your evaluation of the metal might be premature at this time, economically speaking, we ask that you at least begin your preliminary investigations of titanium. Undoubtedly you will encounter some new problems in working titanium for the first time, as is the case when working any new metal. It is well to become acquainted early with any such problems so that you will be prepared when an opportunity arises regarding large scale production of titanium.

Titanium is not a metal which will resist high temperature, although it has a high melting point of 3150°F. It is not practical to consider the use of titanium for long-time high temperature applications in excess of 950°F. Commercially pure titanium can be fabricated with standard sheet metal working equipment at room temperature, providing that the same precaution be taken in working titanium that would be considered as standard practice for the working of 1/4 or 1/2 hard stainless steel sheet. For intricate forming operations, such as drop hammer forming, pressed die forming and deep drawing, it is recommended that the material be formed at temperatures in a range of 500° to 600°F. For intricate forming of titanium alloy sheet we recommend that the metal be worked at 300°F. Commercially pure titanium can be formed by spinning quite

satisfactorily if the metal is worked at a temperature of approximately 800°F.

In closing we wish to advise you that if you care to obtain titanium without a priority in small quantities there is a limited stock of material on hand.

TITANIUM IN ORDNANCE

By: NORMAN L. REED, Industrial Staff Consultant, Ordnance Corps,
Watertown Arsenal, Watertown, Massachusetts

The Ordnance Corps designs, produces and maintains the combat equipment of the army. It is essential that this equipment, unfailingly, give maximum performance under all types of service conditions. These service conditions are, in many cases, much more severe than those encountered in civilian pursuits. At the same time our army must be prepared to use this equipment under battle conditions in any part of the world. The weight of each piece of fighting equipment is subject to scrutiny by those who use it in service and those groups that must transport, including transportation by an airlift system, the items to the combat area.

The factor of safety that the Ordnance designer allows is always low. He cannot build into Ordnance equipment an extra allowance as protection against a certain demand since an extra allowance means greater weight or massiveness. Tests to assure that the designer's minimum requirements are present in the starting material and in the finished product are an everyday occurrence within the Ordnance Corps. On the basis of the preceding demands you can readily believe that we, i.e., the Ordnance Corps, are severe taskmasters when the use of any engineering metal or alloy is considered.

We have put titanium and titanium alloys to work in some Ordnance equipment. We are now building and we will test many more items - all will have to meet the requirements of the using services. The main reason we have considered titanium is its strength compared to its weight. In general terms unalloyed titanium has the same strength and ductility characteristics as unalloyed or low carbon steel. When you alloy titanium you can have the same general characteristics as the alloy steels used for constructional purposes. In either case the use of titanium will allow a saving of as much as 40% of the weight of the steel item.

The army uses an 81 MM mortar in front line combat. The baseplate for this mortar has to be manhandled. We have made, under production shop conditions, the 81 MM mortar baseplate redesigned as a one-man carry (two men were required to carry the steel item). It is made from

1/10" thick and 1/8" thick unalloyed titanium. After the main section is shaped, the forged center cone and the sheet metal spades are added by welding to complete the structure. The baseplate, produced in the production shop, is now undergoing firing tests at the proving ground.

When the army fires its artillery it is often advantageous to obscure or hide the flash or flame emitted from the muzzle. A flash suppressor, screwed to the muzzle end of the gun tube, is the answer to this problem. However, the weight of this component, strong enough to do the job when made of steel, is very objectionable. Recently produced titanium flash suppressors are light enough so that they do not impair gun efficiency, and yet they are sufficiently strong to withstand the forces imposed at the almost explosive rate at which the gun blast occurs.

Field gun mounts have trails to carry the firing stresses to the ground, and anti-aircraft gun mounts have outriggers to prevent excessive tipping during firing. Ordinarily these are of steel. Both of these items are under construction in titanium. Preliminary tests of box girder type beams have been made and prototype outriggers of titanium have been subjected to load tests. If any deficiencies are encountered, redesign and redistribution of titanium components will be accomplished to give, for example, the same deflection (bending) during loading, as the steel counterpart.

Our request for tubular sections of titanium for recoilless rifle or mortar tubes, and for the recoil cylinders of gun mounts hastened to a considerable extent the industrial effort to develop a tube manufacturing process. The needed tubes were not extruded, i.e., they were "squirted" from a short chunky billet of titanium alloy in an extrusion press.

Some of our gun mounts require a frame, much like an automobile or truck frame (chassis). There is currently under design a gun mount or frame that will use alloyed titanium. Current indications are that the new mount will be 30% to 35% lighter than one of equal strength made of steel. Road wheels for similar mounts, made of titanium, have been designed and a contract for their manufacture is being placed.

In the reciprocating parts of an automatic small arms weapon a small steel component made as hard and as tough as practicable managed to hammer itself into a nonusable condition by impact against a fixed portion of the weapon. The component is now made of titanium of the same strength and toughness as the original steel part. It is 40% lighter, and therefore it has less mass and it does not deform under severe service conditions.

Since titanium alloys can be tough as well as have high strength, plates of the material have been subjected to firing or ballistic tests.

It is conceivable that a considerable weight reduction in armored vehicles is possible; if substitution could be done on a gage for gage basis it would be theoretically possible to save 40% on those parts substituted.

Titanium is under consideration for airborne missiles and aircraft components to replace either the heavy stainless steels, or the lighter metals which lost their strength at the temperature levels developed by the friction of these items when moving through the atmosphere at very high speeds.

Bridges constructed of titanium, cylinders for the storage and transportation of compressed gases, and air strip landing mats of this light and strong material have reached the development and planning stage by Department of Defense units other than the Ordnance Corps.

To date in many of the Ordnance applications there has been direct substitution of titanium for steel particularly since the interchangeability of components is necessary until such time as adequate quantities of titanium become available and the economic aspects are satisfactory. This direct substitution is recognized as being less than optimum in some cases. We expect the most favorable results in titanium will be from applications where the design takes into account the difference in characteristics of titanium and steel, and/or the other metals, formerly used. In these cases titanium will be used to its best advantage irrespective of previous designs established for other engineering metals.

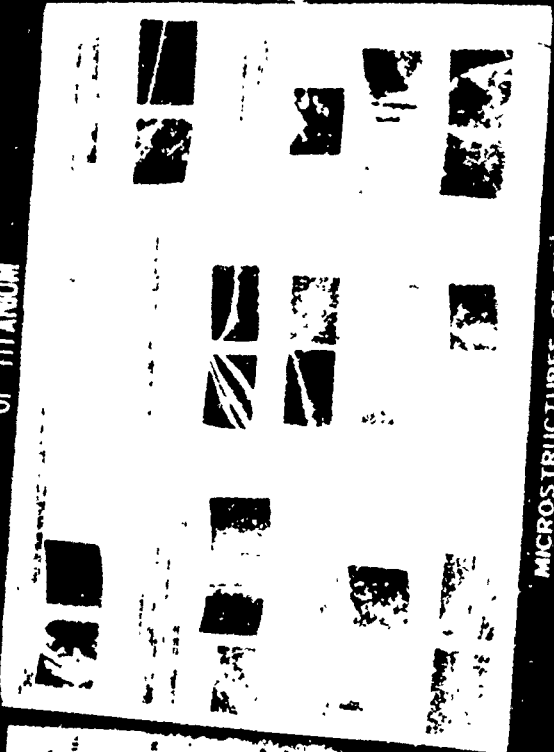
In summary, we have used the titanium produced by the companies represented here today. We have utilized most of the processes that will be described to you by those that follow me on this program. We are pleased with the results and not frightened by the changes in procedure with which we have been confronted in order to produce much lighter weight Ordnance components than we have had in the past from steel or ferrous alloys.*

*Attention was called to a titanium exhibit assembled by the staff of the Watertown Arsenal Laboratory who were in attendance to answer questions. As shown on the accompanying photographs there were individual displays of components, charts and test results pertinent to:

Physical Characteristics of Titanium
Titanium Surfaces - Behavior and Treatment
Processing of Titanium
Casting - Forging - Drawing - Compacting
Commercially Available Products
Ordnance Application of Titanium
Welding of Titanium
Armor Applications

PHYSICAL CHARACTERISTICS
OF TITANIUM

PHYSICAL CHARACTERISTICS OF TITANIUM
Titanium is a lustrous, silvery-white metal with a high melting point of 3040°C (5494°F). It is highly resistant to corrosion and oxidation, especially in the presence of oxygen, where it forms a protective oxide film. Titanium has a low density of 4.54 g/cm³, making it one of the lightest structural metals. It is also known for its high strength-to-weight ratio and excellent fatigue resistance. The metal is ductile and can be easily formed into various shapes. Its physical properties make it ideal for use in aerospace, marine, and medical applications.



MICROSTRUCTURES OF TITANIUM
AND SOME TITANIUM ALLOYS

ALUMINUM TITANIUM
MICROSTRUCTURE

PHYSICAL PROPERTIES

MECHANICAL PROPERTIES

PHYSICAL PROPERTIES

MECHANICAL PROPERTIES

8 OCT 1952

WATERTOWN ARSENAL LABORATORY
EXHIBIT AT TITANIUM SYMPOSIUM

WTN.921-1736

TITANIUM SURFACES
BEHAVIOR & TREATMENTS

TAMM
DRAWING

The collage contains several distinct elements:

- Top Left:** A large circular diagram with a central point and radiating lines, possibly representing a cross-section or a specific surface treatment area.
- Top Center:** A grid of small, square images, likely micrographs or surface analysis results.
- Top Right:** A diagram showing a series of rectangular shapes arranged in a row, possibly representing different surface treatments or material layers.
- Middle Left:** A diagram with a central vertical axis and several horizontal bars extending from it, resembling a bar chart or a schematic of a surface structure.
- Middle Center:** A large, light-colored rectangular area, possibly a photograph of a surface or a technical drawing of a component.
- Middle Right:** A diagram showing a series of rectangular shapes arranged in a row, similar to the top right diagram.
- Bottom Left:** A diagram showing a series of rectangular shapes arranged in a row, similar to the top right diagram.
- Bottom Center:** A diagram showing a series of rectangular shapes arranged in a row, similar to the top right diagram.
- Bottom Right:** A diagram showing a series of rectangular shapes arranged in a row, similar to the top right diagram.

US PATENT
TITANIUM
SURFACE TREATMENT



TITANIUM SURFACES
BEHAVIOR & TREATMENT

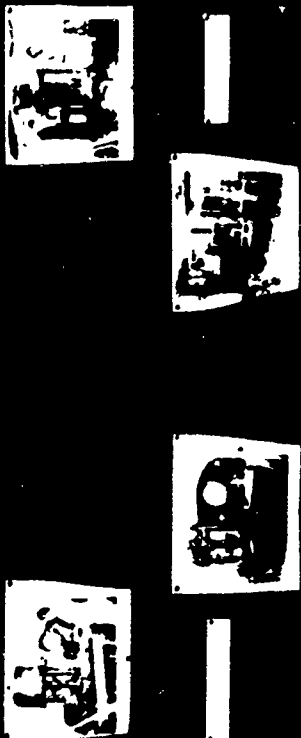
TITANIUM
DRAWING

ANALYSIS OF
TITANIUM

CORROSION

VTN 921-1741

PROCESSING OF TITANIUM
CASTING - FORGING - DRAWING
COMPACTING



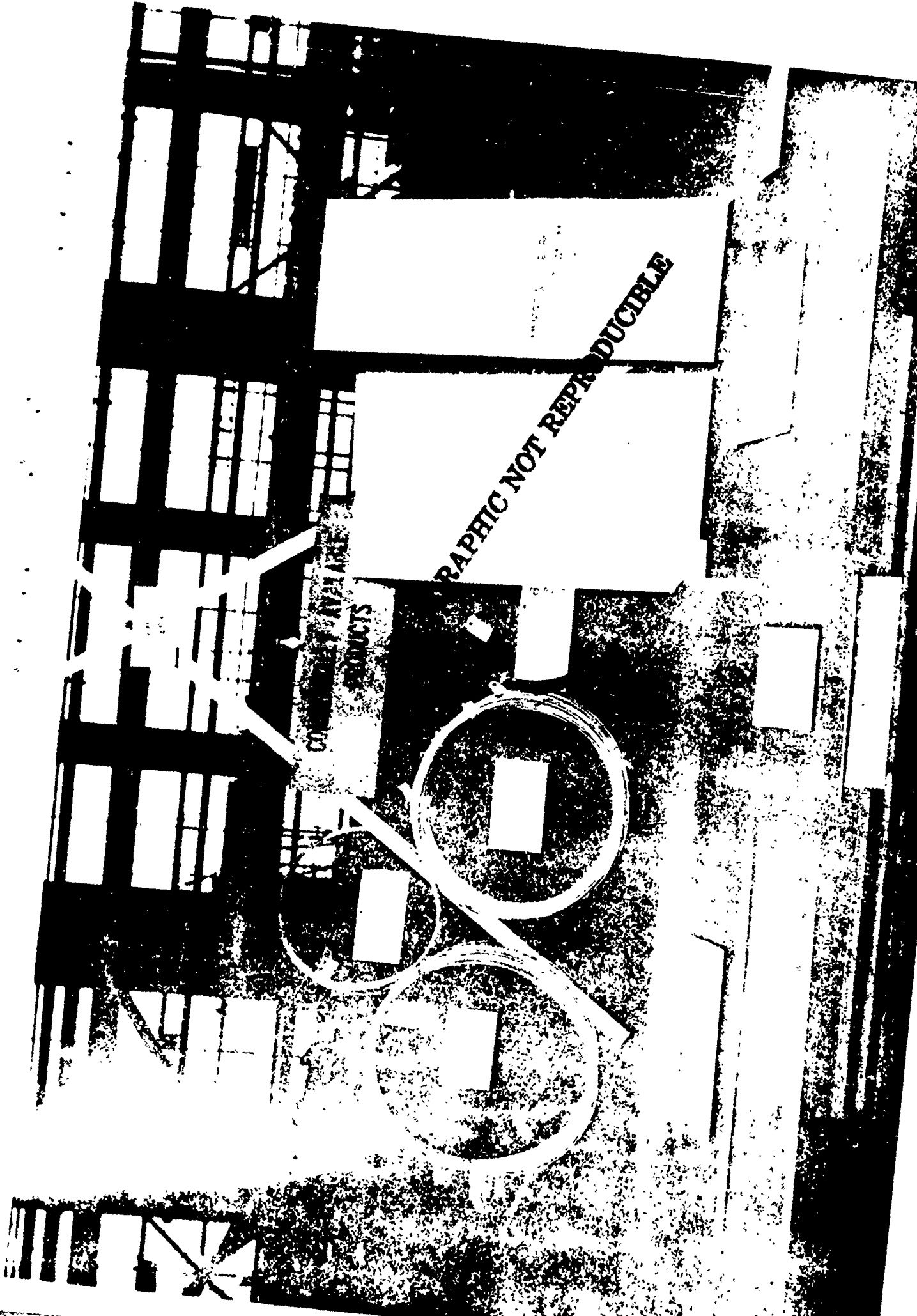
COMPACTING



6 OCT 1952

WATERTOWN ARSENAL LABORATORY
EXHIBIT AT TITANIUM SYMPOSIUM

VTN.921-1741



CONTACT SURFACES

GRAPHIC NOT REPRODUCIBLE

8 OCT 1952

WATERTOWN ARSENAL LABORATORY
EXHIBIT AT TITANIUM SYMPOSIUM

WTU 021-1737



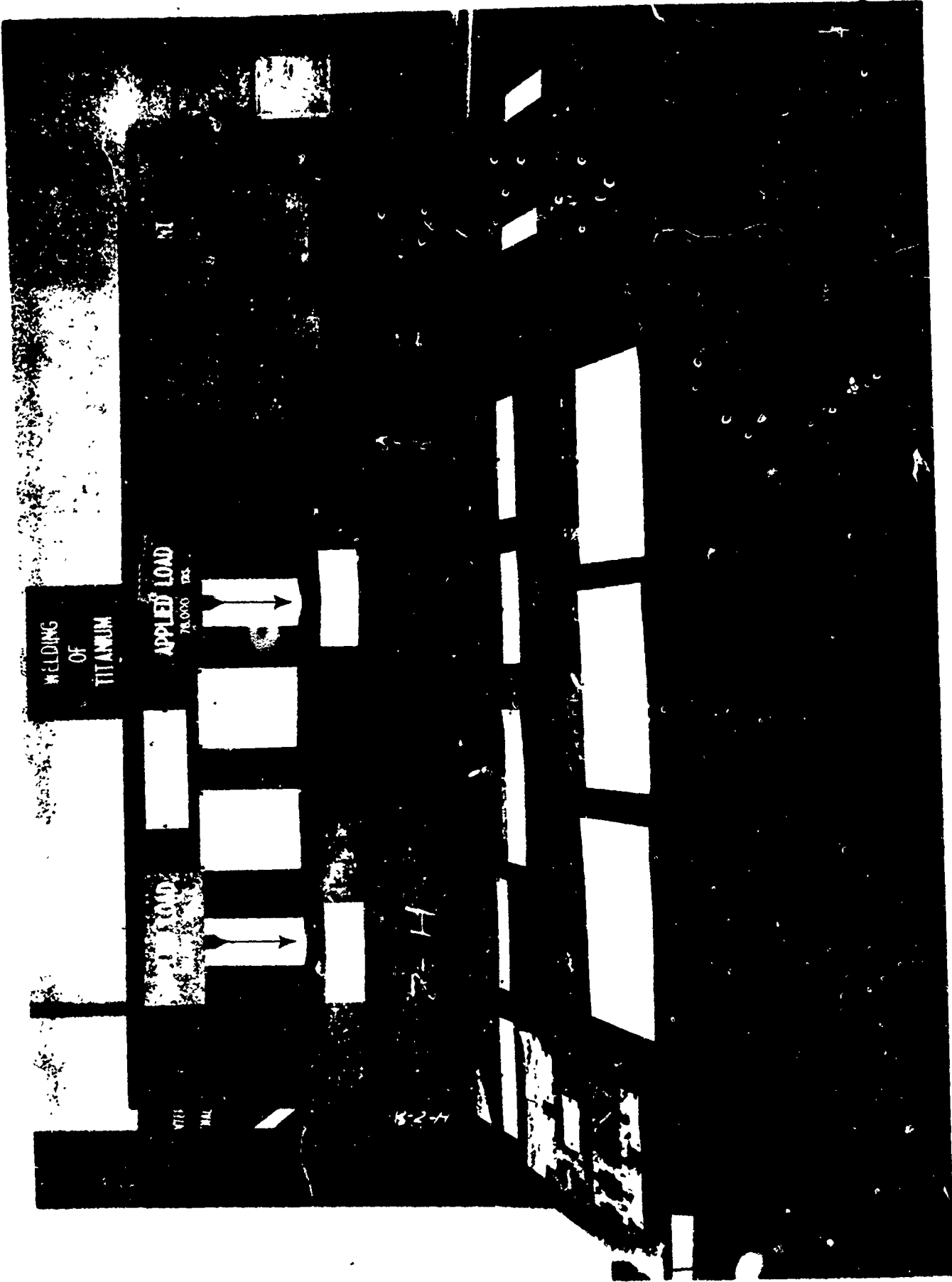
ORDNANCE
APPLICATION
OF
TITANIUM

VTN.921-1742

WATERTOWN ARSENAL LABORATORY

EXHIBIT AT TITANIUM SYMPOSIUM

8 OCT 1952



WATERTOWN ARSENAL LABORATORY

EXHIBIT AT TITANIUM SYMPOSIUM

9 OCT 1952



8 OCT 1952

WATERTOWN ARSENAL LABORATORY
EXHIBIT AT TITANIUM SYMPOSIUM

WTN.921-1743

FORGING OF TITANIUM

By: RICHARD J. BULLOCK, Research & Development Engineer, Wyman-Gordon Company, Worcester, Massachusetts

The purpose of this talk is to present the techniques and experiences of the Wyman-Gordon Company in the making of closed die contour titanium alloy forgings.

About three years ago we had our first opportunity to make a titanium alloy forging. The part was a large compressor wheel weighing approximately 200 pounds as forged. A 200 pound titanium alloy wheel is the equivalent in volume of a 360 pound steel wheel. The forging was 27 1/2" in diameter with a 1.00" thick web, a 3.00" thick ring at the outside diameter, and a 3 7/8" thick ring at the half radius. An integral test ring was incorporated in the finish forging design to provide for 100% tensile testing of the forgings.

The material specified for the wheel forging was a Cr-Fe-Ti alloy. The supplier of this material had no facilities for converting their ingot material to wrought billet, so we were required to accept an induction melted as cast ingot. The ingots were cast in a carbon crucible which produced a very irregular hard layer on the outside of the ingot. Because of the surface defects it was necessary to remove 3/8" from the radius and both ends of the ingot. The rough outer layer was found to be particularly hard on tool life, so a rough grinding operation was initiated preceding the turning operation. The removal of the outer skin by grinding increased the tool life and decreased machining time. In almost all cases the machining operation did not eliminate all of the surface defects. Etching and grinding was necessary to remove the local defects which were not removed in the machining operation. When the ingot was completely free of all visual defects, the forging operations were performed.

The first step in converting the ingots to a finished wheel was to cog the ingot from its starting size of approximately 11" in diameter to a bar approximately 9" in diameter by 19" long. The bar was then upset to a biscuit about 20" in diameter. Heating of the ingot for the cogging and upsetting operation was done in a rotary hearth type furnace fired by oil. The cogging and upsetting was done on flat dies mounted in a 1500-ton hydraulic press.

In the first trial runs we limited our runs to two ingots. Being unfamiliar with the material, care was taken to limit the amount of reduction made with each squeeze of the press; however, as more experience was gained, we were able to process ten ingots through the cogging and upsetting operation in the same setup by drawing each ingot in one heat, reheating and upsetting after the reheat.

The biscuits after spot conditioning were ready for the hammer forging operations. Because of the geometry of the finished part a blocking die was necessary. Both the blocking and finishing operations were performed in 20,000 pound steam drop hammers. The heating of the biscuits was done in a rotary hearth furnace. When up to heat the biscuits were run through the blocking hammer, recharged into the furnace, and run through the finish operation and trimmed. Approximately 75 wheels were forged before this experimental wheel program was completed. The physical properties obtained from the integral test ring of one average forging were: Y.S. (.2% offset) 114,300, T.S. 128,300, Percent Elongation 8.0.

I would now like to go on to our more recent experiences in forging large compressor wheels of titanium alloy. In the early wheel program the number one problem was converting the cast ingots into a forging material. Today the suppliers of titanium alloy are supplying sound billet material ready for forging without press or hammer preworking. At present, we are forging a number of wheels on a semiproduction basis. The wheels range in size from 20" to 25" in diameter and in weight from 80 to 110 pounds.

The two principal alloys that are presently being used for the wheel programs are Ti-150-A alloy and Rem-Cru 130-B alloy. Both alloys are being processed in much the same manner. The material is being supplied as round cornered square, or as turned round. The sizes most used are 9" diameter or 9" square. The cut multiples are heated at 1750°F for both alloys and forged directly in the hammer dies. Test results obtained in very recent runs of both alloys have yielded very good physical properties.

The Wyman-Gordon Company has not limited the titanium forging program to the manufacture of large closed die forgings. Smaller forgings ranging in weight from 13 ounces to 18 pounds have been made on mechanical forging machines, upsetter machines, hydraulic presses and steam drop hammers ranging in size from 1000 pounds to 5000 pounds.

One of the first experimental titanium small forgings which was made at our Worcester plant was an aircraft piston. The tools for this piston were designed for forging aluminum alloy forgings and had been used successfully in manufacturing thousands of aluminum alloy pistons. The titanium alloy selected for this experiment was 6" diameter Ti-150-A alloy. The forging operations consisted of preblocking, blocking and finishing.

Heating of the material was accomplished in rotary hearth type furnaces controlled at 1650°F. The preblocking operation was made on an 800 ton single action hydraulic press. Both the blocking and finishing operations were forged in 5000 pound steam drop hammers. In the two hammer operations, the piece was forged over a plug which formed the

inside diameter and wrist pin bosses of the piston. The draft angle on the plug of the blocker die was 5° and the draft angle on the plug of the finish die 1°. In the forging both the finish and blocking operations, the forging stuck on the plug. In addition to the sticking problem, a phenomenon known as "firing" occurred during the finish forging of one piston. Firing is local burning of the forging material presumably caused by friction between the work piece and die block. Oftentimes this condition may cause the loss of the forging and irreparable damage to the dies. In the case of the piston, we were able to grind out the fire mark in the die and in the piston and satisfactorily complete the forging operation.

An investigation of the feasibility of using slow acting hydraulic presses for the forging of titanium in contour dies has been made. A relatively simple wheel forging 6 3/4" in diameter weighing 13 pounds with a cross section contour shaped like a dog bone was selected for the press forging investigation. For comparison, two wheels were made in a 3000 pound hammer and two wheels were made in the same dies mounted in a 1500 ton hydraulic press. The four multiples (two for the hammer and two for the press) were cut from the same heat of Ti-150-A material.

As near as possible, the processing of the press forged and hammer forged wheels were identical. Heating temperatures, heating cycles, die heating and die lubricant type and amount were controlled to reduce the variables and make an accurate comparison possible. The forging results were quite surprising. Superficially, the press forgings were better than the hammer forgings. A comparison of physical properties showed that the press forgings had higher yield and ultimate tensile values than the hammer forgings, and that the ductility values were about the same.

Small experimental forgings have been made in limited quantities in dies designed for steel forgings. Small shallow die impression forgings present no problem in hammer dies designed for steel; however, if the impression is deep, and the draft angles on male plugs in the die are not greater than 5°, trouble with sticking on the die is very likely to occur.

Hot upsetting in mechanical upsetter machines looks very promising. A few gear forgings have been made on a No. 4 upsetting machine with good results.

Titanium is a clean material with which to work. Unlike carbon and low alloy steels, titanium does not form a heavy scale when heated to forging temperatures. This eliminates the necessity of descaling before forging, and it also eliminates the scale pocket so prevalent in steel forgings. However, titanium does form a scaled surface when heated to forging temperature. This scale is a rust colored oxide which has abrasive qualities and is very hard on machine tools. This titanium

scale may very well reduce the life of die sets in production forging below the number of forgings expected of the same dies in forging steel. This is only a supposition since the number of titanium pieces forged to date in any given set of dies has been far too few to accurately prophesy die life. Another characteristic of the titanium scale is that it adheres to the die surface.

Forgings made in shallow impression dies have a very smooth surface; however, if the die impression is irregular with extreme changes from shallow to deep pockets, a rough surface often results in the portion of the forging formed in the deep die cavities.

Just a word about the shrinkage of titanium forgings. We have had many customers request that a few titanium forgings be made in their die sets which were designed for steel forgings. In many cases, we have produced these forgings on an experimental basis, knowing that the forgings were to be used for investigation of the alloy. In production forging this would not be practical because of the difference in shrink between most common alloy steel forgings and titanium. This difference in shrink results in a 1/8" per foot oversize condition in all directions on a titanium forging produced in dies designed for steel.

In almost all closed die forgings, there is an opening all around the die impression into a cavity called a gutter. This opening is called a flash. Its purpose is to provide a channel for forcing the excess forging material in the die impression out into the gutter to allow the dies to be brought down to the proper closure. The thickness of the flash in steel forging design is generally dictated by the size and the geometry of the forging. This design practice holds true for titanium except that experience has indicated that for a given part, the flash thickness for titanium will be heavier than for the same part made as a steel forging. The reason for this is that the titanium flash as it cools in the relatively thin flash section tends to choke off the avenue of escape for the excess material resulting in a heavy forging in a plane normal to the die parting plane.

Fortunately, titanium forgings trim quite easily at the finishing temperature of billets heated at 1750°F.

Another point to bear in mind is the problem of die heating. In large forgings approaching the capacity of the equipment being used, the working temperature range is quite narrow. Heating of the dies helps considerably in reducing the heat loss from the work piece into the dies.

The resistance to deformation of titanium at a forging temperature of 1750°F is considerably greater than that of SAE 4340 steel at its forging temperature of 2250°F. Compressor wheels of both materials have been forged in the same dies, and in the same equipment. The SAE 4340 wheels were completed in far fewer hammer blows than were the titanium alloy wheels.

A bright spot in forging titanium is its resistance to cracking when being hot deformed. There have been instances of surface defects, which were missed in conditioning the billet material, opening up under the first few hammer blows. Even though the multiples were given severe reductions after the opening of the surface defects, the cracks did not propagate.

In the overall forging picture, titanium does not behave like any other forging material; rather it is a material with its own exclusive forging characteristics.

COLD FORMING OF TITANIUM

By: J. WALTER BULLIKSEN, General Superintendent, Worcester Pressed Steel Company, Worcester, Massachusetts

We heard something of this wonder metal about two years ago and decided that we should investigate it, because after all you cannot ship a customer a carload full of tensile properties, nor a box full of Charpy tests. You have to make something out of the material in order to use these marvelous characteristics. We, therefore, purchased a small supply of the sheet titanium, commercially pure Ti-75-A, and decided to see what could be done. We found that the material had considerable promise, it had good formability, it seemed to possess some of the qualities that would make it suitable for our field. When you consider that titanium is the fourth most abundant metallic element, naturally from our point of view it will never achieve its full destination unless you can make stampings out of it, because after all isn't that one of the most efficient ways of fabricating metal products?

In making stampings it is entirely a condition of cold, plastic flow. The material must be stressed beyond its elastic limit to cause it to flow. It must not be stretched beyond the ultimate strength or it will rupture and so we in the stamping industry have to work between the end of the elastic limit or the yield point and the ultimate strength of the material, and if you will look at the physical properties of commercially pure titanium you will find that there is a reasonable spread between those two values, and this is the no mans land in which we operate. Also titanium has a fairly good elongation, 20% to 30%, and this was hopeful. We tried a piece of titanium in some steel dies which had been used in drawing cups in ordinary cold rolled steel and succeeded in drawing a cup.

This cup, (exhibiting same), was drawn from commercially pure titanium, and we were quite elated to find that the material had the plastic ability to reform in this manner, but our sorrow was great, because we found immediately upon having made the first piece that there was a bad

condition of scratching on the side wall and the die was considerably roughened up. As we proceeded in our tests and our experiments we found that this initial trouble was going to plague us all through our tests, and our problem became just as much one of solving the frictional difficulties as one of causing the material to flow. There is a way in the stamping industry to measure the amount of formability. We consider the diameter of the blank in relationship to the diameter of the cup which is produced, that gives us a ratio and subtracting that from 100% we get a value that is known as the percent reduction. The percent reduction equals 100% minus the diameter of the cup divided by the diameter of the blank. Now for good plastic material it is a good commercial round figure to say that 40% to 45% reduction is a pretty good job.

The first test consisted in a reduction of 34% and was, therefore, quite encouraging. The problem of solving the pickup on the dies next engaged our attention and we used a variety of high pressure lubricants, but these were not sufficient. We then tried bonderizing which consisted in immersing the blanks in a solution consisting of 33 pounds of bonderite in one hundred gallons of water, to which had been added seven ounces of sodium chloride, the entire bath at 160°F and when the blanks were immersed for about ten minutes they obtained a phosphate coating which lent itself very well to the drawing operation. It was in addition necessary to still use a good high pressure lubricant and by this means we were able to reduce the amount of scoring of the dies but not entirely eliminate them.

In attempting our next draw we took a rather large blank of .078" gauge material and reduced it to 2 3/4" diameter. This cup represents our second attempt, and here you see a reduction of 38%. We did something a little different in this case by using a bronze die ampco metal which is supposed to have better frictional properties and is well thought of for drawing stainless steel. However, we found that this was not the answer entirely either, because the assistance we got from the use of the bronze die was not great enough to amount to an answer.

Our next attempt was to see what could be done with successive drawing operations, because it is obvious that if you are limited to some 40% or 45% in the first reduction then you must put further operations on a par in order to obtain longer, smaller diameter shells, and we chose for this experiment a filter case which we normally make from cold rolled steel. This filter case, (exhibiting same), is made in three operations.

First the initial blank and cup which consisted of about 40% reduction from the diameter of the blank to the diameter of the cup. The next operation was a further reduction and this was followed by still further reduction. As the diameter is reduced the length increases. Now we have the general shape and the final striking operation produces

some ribs in the bottom, puts a sharp corner radius at the flange and practically finishes the filter case. Although these operations were done without any intermediate annealing in cold rolled steel, we found that the titanium work hardened so rapidly that it was necessary to introduce an intermediate stress relief between each of these operations. We also were enabled in this particular case to test the value of sintered carbide dies and we found that this was a great help too in mitigating the scoring that takes place. Some of you may wonder why I emphasize this problem of scoring, because after all what difference does a few scratches make. Well conceivably you might be making a product on which a few scratches made very little difference, but the scratches indicate that little particles of titanium are being scraped from the surface of the material and are being cold welded to the die making small nodules, and the next piece that goes through will be ripped, as it were, with a file like surface, and you very shortly reach the end of that type of procedure, so it is mandatory to solve this problem of the frictional trouble which we ran into.

We found that we obtained a very satisfactory stress relief which restored the ductility of the material by heating to 1325°F for a matter of four to ten minutes, depending on the thickness of the material. That was done without any controlled atmosphere, without any quenching, simply an air cool afterwards. The material is not difficult to stress relief, but we run into the problem of scaling on the surface and due to the fact that titanium resists the action of the normal pickling solution it is necessary to descale by means of either the Dupont Process or the Hooker Process, or some other equivalent process in order to restore the surface conditions which are best suited to the deep drawing operation.

I have cautioned you not to think of our procedure in deep drawing as a stretching operation, but rather as a problem in cold flow. When we find that we increase the blank beyond a certain point we no longer can draw a cup through because the punch instead of drawing the material through the die will merely punch a hole where it strikes the material.

When we cannot make a piece flow we cannot solve our problem by going to a larger press. The material will rupture just the same, so it is necessary in the deep drawing to pay strict attention to various small items. These are the key to successful deep drawing. The things which compose the art of craftsmanship involve: making the tools, the radius on the die, the clearance between the punch and the die, the amount of pressure which is used on the blank holder and the surface condition. All of these elements are very important. We have only scratched the surface in developing the answer to these refinements.

Having experimented with these heavier gauges of material we decided to see what could be done with the lighter gauges, and we next experimented with some .037" RC-70 titanium which is another product of

commercially pure titanium, and we made some very small cups in this material. We were able to obtain satisfactory percentages of reduction there also, and in our first draw we obtained a reduction of 40%, which is very good.

The sample which I have is so small that it is not very striking, but this small cup, (exhibiting same), which is only about the size of my finger in diameter and maybe an inch and a half long is made in three successive operations starting with .037" material. We also did the same with .025", three draws each one followed by an intermediate anneal. Then we tackled .016" with the same procedure and we were able to make two draws, but on the third draw we found that the material no longer returned to its former excellent plastic condition and the cups in the third draw split.

I do not feel that this indicated an answer, or the end of such tests. I merely feel that it was expecting a lot by our somewhat crude and undeveloped methods and I think that the problem can be solved when you realize that .016" material is rather thin, and that we carried through two draws and two anneals and finally the third draw resulted in fracture. I think you will agree with me that probably our technique will soon be able to master even this light gauge material.

We feel that we have proven that commercially pure titanium has sufficient ductility to take conventional deep drawing operations with reductions up to a maximum of approximately 40%. We found that the material work hardens rapidly, and where several draws are involved it is necessary to stress relieve between each operation. Stress relieving produces considerable scale, and therefore, descaling is advisable after each stress relief.

One of the greatest problems encountered was the problem of lubrication. Three things were tried which seemed to be the greatest help. The phosphate coating, a brass or copper plate on the material and anodizing. After these treatments it is still necessary to use a high pressure lubricant. Next to the frictional problem the greatest need which we found seemed to be in greater uniformity of the material, because we found that our results were a little bit erratic, and that there were occasions when there were imperfections in the material, and we trust that we may leave this problem in the hands of the producers confident that they will solve them.

SURFACE TREATING AND CORROSION OF TITANIUM

By: GEORGE C. KEIFER, Associate Director of Research, Allegheny
Ludlum Steel Corporation, Brackenridge, Pa.

In applying a material to a given corrosive service many factors other than the normal resistance of the metal to the polar medium

involved must be considered. While there are many commercial metals available today which, purely from a standpoint of chemical activity, are superior to titanium, they require care in fabrication, controlled operating conditions, and special maintenance provisions to avoid failure from causes other than direct attack. It is in this respect that titanium appears to have distinct advantages over many of our present day materials of construction.

The value of a metal as a corrosion resistant material is determined by the following characteristics: (1) Resistance to General Attack; (2) Resistance to Localized Corrosion or Pitting; (3) Resistance to Contact or Crevice Corrosion; (4) Resistance to Intergranular Attack, and (5) Nonsusceptibility to Stress Corrosion Cracking.

On the basis of laboratory tests titanium appears to be less susceptible than many other metals to most of these types of attack, and such advantages should provide industry with a more useful corrosion resistant metal.

Resistance to General Attack - The most important factor in the selection of material is resistance to general attack. Titanium exhibits excellent resistance to a wide variety of corrosive media; in fact, its resistance covers a broader range, from strongly oxidizing to reducing solutions, than most metals. For example, it is practically unattacked by such a strongly oxidizing medium as fuming nitric acid, and yet it has excellent resistance in a moderate reducing environment such as weak solutions of hydrochloric acid. In between these extremes, there are some acids which corrode titanium quite rapidly, but these cases are not too numerous.

The resistance of titanium to the more common mineral acids is shown as follows:

Nitric Acid	Resistant to all concentrations including 95%
Sulfuric Acid	Resistant up to 4% by weight at 100°F
Hydrochloric Acid	Resistant up to 5% by weight at 100°F
Aqua Regia	Resistant up to 100°F
Phosphoric Acid	Not resistant, except to cold dilute solutions
Hydrofluoric Acid	Not resistant
Sulphurous Acid	Unaffected
Chromic Acid	Unaffected

It can be seen that titanium has excellent resistance to nitric acid of all concentrations, including the fuming grades, at all temperatures up to boiling at atmospheric pressure. Its usefulness in this field is demonstrated by an actual service application where it is proving very satisfactory for nitric acid at high temperature and pressure. Where sulfuric and hydrochloric acids are involved, the metal is only resistant to dilute solutions up to 100°F. However, the addition of

small amounts of certain inorganic salts act as excellent inhibitors and where such additions can be made, it can be used in more concentrated solutions at temperatures up to the boiling point. Titanium differs from most other metals where hydrochloric acid is concerned, in that inhibitors are completely effective in preventing even slight attack. The fact that aqua regia does not corrode titanium is an example of the inhibiting effect of nitric acid. Very few metals are resistant to aqua regia.

Resistance of Titanium to Inorganic Salts - Not much data are available on the resistance of titanium to inorganic salts. Most of the information is centered on the superior resistance of the metal to chlorides. It is very resistant to sea water and all inorganic chlorides, including such corrosive substances as ferric and copper chlorides, and strong bleaching solutions such as the hypochlorites.

The excellent resistance of the metal to nitric acid and to dilute solutions of sulfuric acid indicates that it might be suitable for all neutral salts of these acids. There is very little information as yet on the behavior in phosphates or fluorides. It would be logical to assume, however, that in most of these salts very low corrosion rates will be the rule.

Where alkalis, such as sodium or potassium hydrate and the carbonates are concerned, extremely low corrosion rates prevail, in highly concentrated solutions at boiling temperature. Some slight discoloration may result on prolonged periods of exposure.

Behavior of Titanium in Organic Acids - Data on the behavior of titanium in organic acids is limited to the most commonly known, such as acetic and lactic. Laboratory tests show that titanium is practically unaffected in these acids. It is somewhat surprising that it is quite rapidly attacked in formic acid.

Resistance to Localized Corrosion or Pitting - Most commercial metals are susceptible to pitting or some other form of localized attack. Pitting may result from the hydrolysis of a chloride solution, or in some cases a sulfate. It may also be caused by an oxygen concentration cell, a precipitate formed as a by-product of a reaction, or the formation of a foreign deposit on the metal surface. Most of these types of attack can be readily duplicated in the laboratory. The results of pitting tests indicate that titanium has a very high degree of resistance to localized corrosion. Samples of the metal have been exposed to several vicious pitting reagents such as ferric chloride, cupric chloride and sodium hypochlorite for several months and no noticeable corrosion of any type has appeared. These solutions produce rapid and violent pitting in many other metals in a matter of hours. Similarly solutions of sodium chloride and hydrogen peroxide have little effect on titanium, while they will pit certain light metals in a short time.

One of the most severe pitting conditions is encountered when a metal, in contact with carbonaceous or other foreign matter, is exposed to a corrosive environment.

The resistance of titanium to pitting is quite unusual, and from this standpoint alone, should become a valuable material of construction. In many applications where pitting develops due to changes in the acid condition of stagnant solutions, or where salts settle out on the metal surface, titanium should resist localized attack for much longer periods than other base metals.

Resistance to Contact and Crevice Corrosion - Contact and crevice corrosion are additional types of localized attack. In fabricating equipment for corrosive service it often is necessary to resort to gasketed joints or seals. In many cases it may also be difficult to avoid crevices caused by overlaps or corners. These conditions are troublesome sources of corrosion. A number of preliminary tests indicate that titanium is far more resistant to localized attack than most metals when in contact with organic materials like rubber, or when crevices are present.

In regard to the effect of crevices, laboratory tests indicate that titanium is less susceptible than most other metals to localized attack. While a much longer testing period is necessary to determine complete immunity to this form of corrosion, even a short testing period is sufficient to indicate a high degree of resistance to crevice corrosion. This should mean that less frequent cleaning operations under gaskets and in crevices will be required for titanium than for most other metals.

Resistance to Intergranular Corrosion - Intergranular corrosion is not an unusual phenomenon, and is often referred to as caustic embrittlement or weld decay. It is caused by the precipitation of a nonmetallic or intermetallic constituent around the grain boundaries which results in localized attack in this area. Intergranular precipitates often form from exposure in a certain temperature range. There are many simple remedies for avoiding intergranular attack in metals, and it is not a serious problem in most corrosive applications. The possibility of intergranular corrosion is usually present where welding is involved. In any welding operation the metal in the weld zone is exposed to all temperatures varying from the melting point to room temperature. Thus any temperature at which a precipitate may form exists in the weld zone. It is, therefore, important to determine the corrosion resistance of welds and adjacent areas.

Tests were carried out in which welded samples of titanium were exposed to various corrosive media ranging from boiling nitric acid to ten percent ferric chloride. No deterioration of the weld or adjacent areas resulted in any of these tests. The ferric chloride test has been in progress for two and one-half years. In addition, samples

of unwelded titanium have been aged at various temperatures for periods up to 500 hours and no marked loss in corrosion resistance was found when tested in boiling 65 percent nitric acid.

The corrosion rates of the samples after several aging treatments were:

Time at Temperature (Hours)	Temperature		
	400°F	800°F	1200°F
24	.0002	.0002	.0003
48	.0002	.0002	.0003
100	.0002	.0002	.0004
500	.0002	.0001	.0004

It appears from the results of these tests that titanium may not be susceptible to intergranular corrosion. However, it often is difficult to select the right environment for producing intergranular corrosion in a certain metal, and additional tests will be required to provide a more definite answer.

Nonsusceptibility to Stress Corrosion Cracking - Stress corrosion cracking of many metals is very much akin to intergranular attack except that failure is of a physical nature. In other words, while the attack is usually intergranular the material actually cracks with no evidence of severe corrosion. Stress corrosion cracking occurs only when a metal is under stress in a selective corrosive environment. Similar to intergranular corrosion, stress corrosion cracking requires a solution or environment which will selectively attack areas usually around grain boundaries. Numerous tests have been carried out on stressed samples of titanium. The tests are in the form of horseshoe shaped samples which are held under tension by forcing and holding the ends in a channel. In addition Erichsen cup tests are also used.

Negative results were obtained in the following solutions after several weeks exposure: (1) 20% sodium chloride plus 1% ferric chloride boiling; (2) 20% sodium chloride plus 1% cupric chloride boiling; (3) 20% sodium chloride plus 1% silver chloride boiling; (4) 20% sodium chloride plus 1% nickel chloride boiling; (5) 20% sodium chloride plus 1% mercuric chloride boiling; (6) 20% sodium chloride plus mercurous chloride, saturated boiling; (7) 20% sodium chloride plus 1% zinc chloride boiling; (8) 20% sodium chloride plus 1% potassium permanganate boiling; (9) 20% sodium chloride plus 1% sodium dichromate boiling; (10) Saturated solution sodium chloride boiling; (11) 20% sodium chloride plus H₂SO₄(pH 0.3) boiling; (12) 20% sodium chloride plus H₂SO₄(pH 1.5) boiling; (13) 20% NaCl plus H₂SO₄(pH 3.1) boiling; (14) 20% NaCl plus 3% hydrogen peroxide room temperature; (15) 20% ferric chloride room temperature; (16) 42% magnesium chloride boiling; (17) 20% salt spray 90-95°F; (18) Sea water

(synthetic) room temperature; (19) 65% nitric acid boiling; (20) 10% sodium hydroxide room temperature; (21) 50% nitric acid plus 5% copper sulfate boiling; (22) 90% white fuming nitric acid room temperature; and (23) Aqua regia room temperature.

The reagents used in these tests are a wide variety of corrosive media, including many which are standard solutions used for stress corrosion testing of other metals. The resistance of titanium to cracking in these solutions provides a good indication of its value as a material of construction. Its general corrosion resistance in chloride solutions is excellent, and its apparent resistance to stress corrosion provides an advantage over some of the commonly used metals which are susceptible to cracking. The behavior of titanium in the 20% ferric chloride solution is quite striking, as this reagent is a vicious pitting medium, often a source of stress corrosion failures.

Cracking in Red Fuming Nitric Acid - The one solution found which produced cracking in stressed samples is red fuming nitric acid at room temperature. The test samples were totally immersed and time for cracking varied between 3 and 16 hours. Cracking also occurred on samples exposed in the vapors alone after several weeks exposure. The red fuming nitric acid was of Reagent Grade, Sp. Gr. 1.60, and contained 20% NO_2 . In addition to these tests numerous cracks were also found around stencil marks on unstressed samples after several weeks exposure in the red fuming acid. While the fuming nitric acid tests indicate that titanium is susceptible to stress corrosion cracking, it is liable to occur only in a particularly selective environment, and under very high stress. However, one of the advantages of titanium is that stress relieving can be carried out at a relatively low temperature, around 1000°F , and such treatment avoids the possibility of stress corrosion cracking.

It can be seen from the numerous laboratory tests that titanium appears to have a promising future as a competitive corrosion resisting material. It has excellent resistance to a wide range of chemicals, and in addition has other attractive characteristics which will simplify the fabrication and maintenance of equipment for the chemical and allied industries. Of course, more experience with practical applications will be required to confirm laboratory findings but it is believed that the behavior in service will closely parallel the various corrosion tests mentioned herein.

The need for special surface treatment, other than those required for appearance or decorative purposes, has not been definitely determined. Some work has been done on anodizing, but the effect of such treatments on corrosion resistance is inconclusive. Titanium in itself has the ability to form a stable protective surface condition. This surface can be made active by immersion in hydrochloric acid or by abrading with emery paper. Boiling in 20% sodium carbonate also causes

an active condition, but it is of a lesser degree. The time for changing from activity to passivity is determined by the activating procedure. Hydrochloric acid produces a very low potential and more time is required to reach a normal passive condition than when the material is activated by the other methods. The maximum potential is shown in relation to a saturated calomel cell. The potential in relation to other metals lies somewhere on the noble side of copper, thus it is apparent that the normal surface condition indicates good corrosion resistance, and that anodizing may not be required except in some isolated cases.

No simple acid pickling solutions for removing scale caused by welding or heat treatment has been developed. The most successful method known is a two-stage treatment involving a molten caustic bath followed by an immersion in an acid solution. The metal is first immersed in a molten caustic bath (there are several different varieties of proprietary baths) for 5 to 10 minutes and then quenched in running water. This treatment is followed by a dip in sulfuric acid to neutralize the caustic, a water rinse, and then an immersion in a solution of nitric and hydrofluoric acids for several minutes. The metal is finally rinsed in water and scrubbed. Depending on the type of scale, immersion in a 5%-10% solution of hydrofluoric acid followed by a whitening dip in nitric acid can be used. The removal of scale is generally necessary when any spot welding is involved.

Methods and materials for mechanically polishing titanium have not been definitely established. The more commonly used abrasives are not completely satisfactory because of the tendency of the metal to drag. This materially reduces the cutting efficiency of the abrasive belt or wheel and after several passes, results in a spotted, smeared surface. Most satisfactory results are obtained by slow polishing speeds using oxalic acid as the lubricant. There are a number of manufacturers of polishing materials working on this problem, and more efficient methods will no doubt be developed.

The corrosion resisting characteristics of titanium are sufficiently good to warrant consideration for many applications where other materials involve costly fabricating or frequent maintenance. Its normal corrosion resistance is of a high order of magnitude and may make possible new processes which are awaiting a material more satisfactory than those presently available.

WELDING OF TITANIUM

By: **ALLAN J. ROSENBERG**, Welding Engineer, General Electric Co.,
West Lynn, Massachusetts

There are two obvious but rather important points which should be taken into consideration if a successful approach is to be made to

the practical welding of titanium. The first is to know the material to be welded, and the second, to know what can be expected from the welded joint. Knowing the material, knowing what to expect you are neither amazed when a weld in RC-55 bends 180°, nor disappointed when one in RC-130-A bends only 5°.

For purposes of discussing welding characteristics of sheet metal I should like to group the various titanium alloys into three convenient categories: considering first, the low strength, commercially pure materials, RC-55 and Ti-75-A; then, the medium strength oxygen-nitrogen-carbon alloys, RC-70 and Ti-100-A; and finally, the high strength, high alloy materials, RC-30-A and Ti-125-A.

It should be mentioned that the various heats of materials which fall within specification in any one of these three groups have a rather wide range of strengths, and it may be considered a "property" of titanium, so far at least, that the higher the strength level the lower the ductility.

In discussing the welding of these materials, I should like to make a further separation -- this time by the welding processes to be used with them. The first process to be discussed is arc welding. Since all the titanium alloys have a marked affinity for oxygen, hydrogen and nitrogen at temperatures above 1000°F, the materials must be protected from the effects of air during welding. With the current status of welding techniques, this limits all arc welding to that done with the inert gas shielded arc. Even with inert arc welding, extreme care must be exercised to insure adequate gas coverage and protection of the weld surface and the weld underside. Contamination by oxygen and nitrogen is detrimental in that a hard, brittle surface layer results with a subsequent loss in ductility. As far as the underside is concerned, tight metal backing is satisfactory, but inert gas backing is much preferred. A feature of titanium which is extremely helpful is the bright, mirror-like surface indicative of proper shielding, and the yellow to blue to grey color of the oxide when coverage is slightly inadequate.

Improvements in gas coverage which are helpful in insuring optimum welds can be achieved by modifying the electrode nozzle so that an extension is used to trap and hold the inert gas over the joint already welded. Welds made with argon, helium or mixtures of the two gases showed no apparent differences in joint properties, so that either gas (or both) may be used successfully.

A standard tensile test is not sufficient alone to give a true picture of joint properties. In a material in which the weld area is low in ductility but high in strength, failure often takes place outside of the weld zone. The tensile elongation as measured in a two inch gauge length is reduced by only a few percent from that of an

unwelded piece, although the weld itself may have almost no ductility. In order to overcome this definite drawback as much as possible, standard bend tests were used in conjunction with tensile results to fully evaluate welded joints.

For both of the commercially pure grades of materials, RC-55 and Ti-75-A tensile properties and bend properties of the welded joints were completely satisfactory and comparable to the parent materials.

In the case of the oxygen-nitrogen-carbon alloys, RC-70 and Ti-100-A, however, there is a drop in bend ductility. While tensile properties of the welded joints are comparable to the parent material, the bend angle suffered an almost 50% reduction after welding. However, if the lower bend angle and its significance in terms of lower ductility are recognized, the materials can and, for that matter, are being used with success. A point worthy of mention for oxygen-nitrogen-carbon alloys is that ductility is drastically lost at carbon contents greater than .25% - possibly because of the precipitation of continuous networks of carbides in the weld. Neither of these alloys, however, has that high a carbon content.

With the high alloy materials weld bead appearance is again excellent, but the welds themselves are exceedingly brittle and several samples of butt welded RC-130-A cracked transversely across the weld upon cooling to room temperature. Because of the extreme loss in ductility in these high alloy materials they cannot, at this time, be recommended for practical arc welded fabrications -- although improvements through heat treatments or grain refinements may be possible in the future.

There is some evidence that heating alone of the parent material even in a vacuum without welding will result in drastic losses in ductility. Several samples of high alloy titanium were subjected to heating and cooling cycles at 1800°F under vacuum conditions and the bend angle was reduced from 180° to approximately 50°.

If cooling was done in air, rather than in vacuum, the bend angle was further reduced. Time at temperature was also a factor so that it seems apparent that recrystallization, grain growth, contamination and grain orientation all contribute to lowering ductility in welds.

All of these materials can be spot welded at a wide variety of machine settings and tensile shear strengths are all comparable to spot welded joints in other materials of comparable strengths, but the ductility is lower, especially with the high alloy grades.

Spot welding tests conducted on RC-55 and Ti-75-A indicated that, within limits, machine variables had little effect on weld properties.

Cross-sections were sound and tensile shear results were excellent at several different machine settings. Failure was generally of the button type. This type is one in which the parent metal tears away from the weld and is naturally more desirable than a straight shear failure, where the break occurs through the weld along the faying surface.

The question of joining titanium to other materials always comes up. An attempt to join RC-55 to an austenitic stainless steel was unsuccessful. The combination broke apart with very little applied load, and the grain structure was extremely coarse and brittle.

Since higher strength materials are more desirable for production parts, more extensive tests were conducted with the medium strength materials RC-70 and Ti-100-A. Both were spot welded just as readily as the commercially pure grades with average tensile shear strengths naturally somewhat higher. Welds were made and tested at three different weld times: 3, 8 and 12 cycles, respectively, but no differences were observed in either weld strength or type of failure, when current was adjusted to maintain weld size.

Etching techniques are very important to obtain a true picture of weld size. There are three distinct zones in a spot weld. The weld itself, the immediate heat affected area and a secondary heated zone. Unless proper etching and lighting techniques are utilized, it is difficult to distinguish between the immediate heat affected zone and the weld itself. This immediate heat affected zone is one in which recrystallization and grain growth has taken place, while the secondary zone is one in which recrystallization without significant growth has occurred.

While the welds made at the three time cycles tested showed little difference in size, there was a difference in the heat affected area. For the weld made at 12 cycles, the appearance is a normal elliptical pattern. The 8 cycle weld indicates the effect of cooling and is more rectangular in shape. The 3 cycle weld has an even greater indentation. Since failures occur around the edge of the weld, it is my opinion that the smaller the heat affected zone the less the area of lowered ductility, the better the welded joint. I would, therefore, suggest short weld times, and while 3 cycles may be too short for consistent production work, 8 cycles is practical.

Only limited spot welding tests were conducted on the high strength material RC-130-A. While the welds were sound, the ductility was markedly reduced. Tensile shear failures were of an extremely brittle nature and samples failed abruptly in test in contrast to the more gradual tearing with the lower strength materials. With the exception of these higher strength materials all of the alloys discussed have been satisfactorily resistance seam welded. Welds were sound and free from cracks or defects of any kind.

A general observation about resistance spot or seam welding for production may be useful. This is the need for uniformly clean surfaces. We have had good luck with removing light scale (700°F) but annealing at 1100-1300°F results in a scale which has had to be removed mechanically. There is tremendous need for shop cleaning methods to produce the finishes required and that is one of the jobs our chemical people are working on now.

Flash welding shows the most promise for joining these materials to date. Another manufacturer has even successfully flash welded titanium to other materials. Flash welding is best accomplished by machines which facilitate rapid pickup and burn-off to prevent excessive oxidation. Because of the tendency of molten titanium to absorb oxygen and nitrogen, protection against such absorption by inert gas coverage should also improve flash weld ductility. In general flash welding results in a more ductile structure than inert arc welding because of forging action and inherent grain refinement of the process. In the case of the high strength materials, flash welding may be the only feasible way of joining.

Just a few words about gas cutting. Gas cutting of titanium or titanium alloys with conventional gases and torches is an exceptionally fast operation. In fact, cutting speeds may be as much as ten times that normally used for the equivalent thicknesses of steel with excellent appearance.

In conclusion, you can see that titanium is a good material. Somewhat less ductile than stainless steel, somewhat lower in fatigue levels, but readily welded in the low and medium strength alloys, and certainly usable.

GRINDING OF TITANIUM

By: GORDON T. RIDEOUT, Chief Field Test Engineer of the Norton Company, Worcester, Massachusetts

It was not until 1950 that the Wyman-Gordon Company began to forge wheels from titanium ingots which weighed around 350 pounds. They were turning the skin from this ingot and it required several hours time. We were requested to see if grinding would remove it quicker. We found that what required a number of hours to turn could be ground away in about 20 minutes. We also observed that snagging with a swing frame grinder was accompanied by an unusually high rate of wheel wear.

We set up what we called the grinding ratio value, known as "G." "G" is the ratio of metal removal in cubic inches per inch of wheel wear. When we first ran samples we did not obtain a very high rate of effectiveness with the wheel; the metal removal was low; wheel wear was high, and we got what we called a grinding ratio of .7.

We decided that the thing to do was raise that grinding ratio value, if we were to do anything at all commercially with titanium as a material. The first test showed that we could raise the value from .7 to 2.5 by reducing the wheel speed. That was the first secret we came out with; that was a threefold increase in the effectiveness of the grinding wheel. Finally, the large improvement came when we discovered that the chemistry of the fluid at a particular grinding speed was the most effective instrument. Therefore by finding the best combination of wheel speed methods and chemical fluid, we have been able to raise the "G" value, the grinding ratio, from .7 to about 15 or 20 times better than we had two years ago.

To compare titanium with tool steel, with which you are familiar, let me say that the "G" value for a high vanadium, high speed steel is from .4 to 1.0. That would be Vasco Supreme, BR4, Vitro steel or the like. On high carbon, high chromium steel, the "G" value is 3 to 4; the regular 18-4-1 high speed steels will be in the neighborhood of 4 to 12, and the common carbon steels and low alloy steels will be from 40 to 80. The value at which we have arrived for titanium is now around 15. That shows we can do a little better grinding job on titanium than we can on some of the ordinary high speed steels but cannot duplicate the ease with which we can grind the carbon steels.

In an ordinary grinding operation on steel, the wear by attrition is very low, and the wear by breaking down of the abrasive bond is usually high, therefore, we have found that grinding titanium is quite different from grinding steel; the attritious wear is exceedingly high, and the wear of the wheel by ordinary means of fracture is negligible.

As we discovered by reducing the wheel's speed, the temperature of the point of contact was lowered and as this temperature is reduced a decrease occurs in the attritious wear.

The chemical factors are more important than the mechanical factors in the operation of grinding. We have done most of our experimental and field test work in the surface grinding category, however, there are other grinding operations which can be studied but we chose this surface grinding category to get our basic information which we pass along to you today. This is the first time that we have made a progress report on the chemistry of grinding titanium. These other grinding operations which are currently running in the field are cylindrical, centerless and internal. There are indications that low wheel speeds are needed and a benefit in those particular cases, however, not enough field testing has occurred to give a definite recommendation on those particular operations. We have done most of our work with vitrified wheels, we know the results, but with organic wheels such as resinoid bonded products, we have no results to date. It is presumed that they may coincide, however, in the snagging operations which we have done, organic bonded wheels are used, and while the wheel wear was extremely rapid, the

dimensional tolerance necessary was not affected by the wheel wear and, therefore, was not a significant problem. The problem in that case was - "Can you grind the material; can you do it without losing the entire wheel plate?" We could, but even so the wheel wear was very fast.

Now just to talk about the grinding fluids for a few minutes. This work was done on titanium Ti-150-A, (Rockwell C 38). We used 69 brands made by 16 manufacturers, plus 22 experimental fluids. They included water solubles, synthetics or nonpetroleum compounds and rust inhibitors, grinding oils, water, air and carbon dioxide. We found this -- that the effect of the concentration of the water solubles was very important. As you increased the concentration going from zero (plain water) to 100 pounds, the grinding ratio "G" increased. In other words, for plain water, we got a 1.4 ratio and for 100 pounds it was 4.0; however, the 100 pounds ratio is likely to invert and to be unstable so for the basic study we used 10%, that is by volume. 10% gave a value of 2.4. Therefore, the results were all on this particular basis of 10% by volume.

Our preliminary study was done at 2500 surface feet per minute in surface grinding. We found that the best of these fluids were as follows:

The rust inhibitors ran from 5.0 to 5.6; best water solubles ran from 3.2 to 4.0; the best grinding oil ran from 6.3 to 6.9; water was 1.4; air, 2.0 - that is, just grinding without any fluid - and CO² was 1.9. In all cases, except the CO², the work was flooded. In the case of CO², we used nozzles with about .016" orifice. CO² was of no value in the grinding operation; you may find it different in the case of machinings.

The most suitable brands we can mention at this time are as follows, in alphabetical order and by the manufacturers' names. This list should help to reduce your research work.

OILS: Cut-max 206
Vantrol 5363A

Essolene S320
Economy 2148

RUST INHIBITORS:

Economy #1500
International 47 LS
Socony-Vacuum Inhibitor A

SOLUBLE OILS AND SYNTHETIC COMPOUNDS:

Koka
International 152R / 58
Rustlick L825
Vantrol 630
Sunoco Emulsifying Oil B

We are not sure what factors of the chemical make-up of these fluids affect the grinding ratio; we do not know enough about the chemistry of these fluids. When sulphur in the oil was present, it may or may not have an effect. It did not seem that way to us. Plain mineral oils were of no value. As the viscosity of the oil was increased that is to heavy oil the "G" value increased, but we did prefer to use the light oils because of chip settling. The highest values of "G" were obtained with oils having a viscosity of between 50 and 150 seconds.

Of the rust inhibitors the nitrite amino type were effective. We do not understand just what happens, but we did find that the plain sodium nitrite in water was just as effective; however, a plain amino added to water was no good. The amino may have some buffering action to keep the alkalinity stable.

In the case of the water base compounds, so little is known about them that it is very difficult for us to come to any conclusion as to the chemistry. A certain few were superior because they were chemically active. It is our theory that the chemistry of the fluids is one to contaminate the surface of the freshly ground titanium. Hitherto we had been interested in lubrication or cooling. We now have an idea that is quite the reverse. Therefore, we say that titanium grinds unlike steel. Anything that you have learned concerning the effective grinding of steel does not apply in the case of titanium.

There are some shortcomings with some of these fluids. The straight grinding oils provide a fire hazard if they are used at conventional wheel speeds; i.e., in the neighborhood of 6000 surface feet; however, if you reduce the wheel speed, you also reduce the spark stream, and the grinding fluids are effective even if you go down to 2500 or as low as 1800 which was found to be optimum condition for some of the grinding oils. The water base compounds, of course, were no fire hazard. There we used the 10% solution and in that case, there is no particular fire hazard. Ten percent solution of these rust inhibitors probably would do no more harm than to dry the skin. We have been using them for several months as have also some of the large manufacturers making parts, and they have had no undue experiences.

What's the effect of the wheel speed on the grinding solution? So far the results discussed have been at about 2500 wheel speed, but this is what happens when we change the wheel speed to find out the optimum speed. With the grinding oil we found that the optimum speed was 1800 and the "G" value increased from the previous value of 6.7 to 15. In the case of the rust inhibitors, it was increased from 5.6 to 13, when we dropped the speed from 1300. In the case of the best soluble oils there was not very much of a change. The best recommendation is that you use either the rust inhibitors or the grinding oil.

What happens to the wheel specifications in this particular procedure? We found the highest grinding ratio was obtained with 32 alundum, a very pure kind of aluminum oxide. Silicon carbide previously had shown some preference in certain operations. We found in all cases that comparison of 32 alundum with silicon carbide showed the former to be a better material which gave a higher grinding ratio. There was one exception and that was with silicon carbide and straight oil at conventional speeds; however, at conventional speeds there is quite a fire hazard when grinding titanium. It is very pyrophoric. It is quite likely to cause a fire, as has been the experience of a few manufacturers. Therefore, when you reduce the speed, the straight grinding oil and the silicon carbide are no longer satisfactory. The aluminum oxide wheel stands on top.

We found that there was an optimum grit size. It increased as we got toward 60 and 80 and began to decrease at 100. So use 60 or 80 grit. As the hardness in the grade of wheel used was increased, the grinding ratio increased. In other words, use as hard a grade as you can without burning or smearing the material. Where you might be accustomed to using H and I grade of wheel, J and M grade of wheel can be used with the lower wheel speed. That is, the grade M wheel can be used when the rust inhibitor is 10% and the wheel speed low. Concerning the structure of the grinding wheel, No. 8 proved to be better than any of the others, such as 5 or the porous type wheels.

We were using wheels at 1600 surface feet per minute and the 10% solution of rust inhibitor; "G" value increased as the table speed increased, and then dropped off. The optimum was at 200 inches per minute.

The downfeed to crossfeed relationship is important for rate of production, as the volumetric removal is important. For a given volumetric rate of removal, use heavy crossfeeds. For high production rates, perhaps you may have a condition which gives you a very high grinding ratio, but it may be too slow for the production rate you have set up. You can reduce the grinding ratio somewhat by increasing your rate of speed, and suffering a little bit on the tolerance, however, as you approach size, you can begin to reduce the downfeed and clear up with very little downfeed.

This might indicate that it would be a desirable thing to put an upper limit on the hardness of the material, otherwise, you will get into grinding and cost difficulties.

We found that RC-130-B and Ti-150-A ground alike although their alloying elements were different. Whether rolled, perpendicular or crosswise, the grinding properties did not change, the characteristics were the same.

Because of the fact that titanium is nonmagnetic you cannot use your magnetic chucks, therefore, one should find better ways of fixturing, of holding the equipment on the surface grinding or grinding machines. In the case of thin, small articles perhaps you can use pressure sensitive tape and because it is difficult to grind, you would expect to get a rougher finish. For stock removal, the smoothest finish was generally accomplished when you obtained the best grinding conditions, i.e., when you got the highest grinding ratio, you also accompanied that operation by the best and smoothest finish. Normally, under conditions previously described, the finish would be in the neighborhood of 35 to 45 micro-inches, using a rust inhibitor with 10% solution, 1600 surface feet, $\frac{1}{50}$ " per minute in a $\frac{1}{50}$ " crossfeed, and $\frac{1}{1000}$ " downfeed with a 32 AFS X8 VDE wheel. You can also get the same results using oil. - You can obtain 25 micro-inches in your reading on the profilometer by reducing the crossfeed and nothing else to $\frac{1}{40}$ ".

Then when you come to finish grinding, if it is necessary to have a finer finish, dress the wheel finely, and you can get 15 micro-inches finish; however, we have found that fishtails will occur when you are attempting to obtain good finishes. In making some samples for the coming metal show, we found this to be quite true. The elimination of fishtails is difficult, perhaps it can be done by raising the wheel speed slightly - in some cases from 1600 to 2000 - that was all that was necessary; filtering the fluid had not much to do with it. It seems to be caused by a particle of the wheel breaking away at the time of grinding, and not a particle that is being recirculated, as is commonly the experience in the grinding of steel. Another thing was to reduce the downfeed to $\frac{1}{10}$ of a thousand; that helped to obtain 15 micro-inches finish.

The point is this, there are many pieces of equipment in use which have conventional speeds and which it is going to be difficult to change to the lower speeds. We have prepared specifications which are currently being used on conventional equipment, that has been published previously. The few editions which we have will come out in the paper, which is due in another two weeks. Those I won't repeat here, but they will cover cylindrical, centerless, internal, cutoff, snagging, barrel-finishing (that is, tumbling), polishing and buffing. You can accomplish with conventional speeds a fairly satisfactory result, but it may be more costly and ineffectual.

Finally, we believe there has been considerable progress made in raising the grinding ratio 20 times in the last $1\frac{1}{2}$ to 2 years. Use low wheel speeds, study the chemistry involved, use the proper methods to get your optimum conditions, and you can do a satisfactory grinding operation on titanium.

TAPPING OF TITANIUM

By: V. JAMILKOWSKI, Tool Engineer, Hanson-Whitney Company,
Hartford, Connecticut

Tapping of titanium, as in other high temperature jet engine alloys, presents problems in machining which are natural to this function. Most users of tools are familiar with these. They are the type which may be observed when a tool is working in a confined space. The difficulty usually is in cooling and lubricating the cutting teeth, and in disposing of the chips which clog the flutes.

In addition to the natural problems incurred when threading a hole, titanium presents several characteristics and properties of its own which make it difficult to tap, namely, its ability to work harden; its tendency to adhere to another surface when rubbed against it - which we call galling, loading or welding; its high tensile strength, and its thermal qualities, such as its low coefficient for expansion and its poor heat conduction. For successful tapping in titanium, it, therefore, becomes necessary to compensate for these characteristics and properties.

Work hardening is caused by pressure developing between the tool and the work when removing the chip. To help reduce this, tools must be kept sharp, clearance and rake angles must be maintained and an oil is necessary to provide a lubricating film between the chip and the tool, as well as between the tool and work. This oil also must act as a cooler.

Galling, loading or welding is caused by metal-to-metal contact. For this condition, the same solution will apply as for work hardening. Also, it is usually a good idea to check for the hardness of the tap.

High tensile strength is a property of the metal which makes it difficult to separate the chip from the material. Because of its high tensile strength, greater pressures than ordinarily are developed as the tool presses into the work, and removes metal as a chip. Also, since the chip is deformed when it separates from the parent metal and slides across the base of the tool, it creates heat. The correction here is obvious, that oil is necessary to reduce friction between chip and tool, thereby reducing heat, also, to act as a cooler for heat which is generated.

In thermal qualities we must contend with the low coefficient of expansion and poor heat production. If heat is allowed to be generated during cutting action, and is not carried away by a coolant, it will be absorbed by the tool. As the tool heats up, it will expand. Since the titanium does not heat up as much and does not expand as rapidly, it will be allowing a condition to develop where the tool becomes larger

than the hole it has cut. The solution here, again, is to keep the cutting temperatures down by having sharp tools and correct lubricant. Additional requirements are: (1) proper machine tools, (2) pretapping machining, (3) correct tap design and manufacture, and (4) suitable lubrication.

(1) Proper Machine Tools and Equipment - It is very important to have rigid equipment - that is, equipment in good condition. Fixtures must be provided to hold the work securely. The tools must be positively driven and under no condition, should the drilling or tapping stop or hesitate once it has started. Because a positive drive is necessary, friction tapping heads that permit slippage are not suitable.

(2) Pretapping Machining - An important step in the tapping of titanium is in the machining of this material before any threading is done. The surface in the hole and around the edge must be kept as free from work hardening as possible. In tests conducted in our plant we used standard high speed steel drills. These were resharpened and surface heat treated to obtain extra skin hardness. The included point angle was between 130 and 137°. The lip clearance or backing off of the cutting edges was 10 to 12°. These drills were size Q, which is .3320" in diameter. They were operated at a spindle speed of 225 RPM, which is approximately 20 surface feet a minute, and at a speed of .006" per revolution. The lubricant used was sulphur concentrate which is a sulphurized lanolin in paste form. It was observed that these drills performed satisfactorily. Subsequently, we used high cobalt, high speed steel drills sharpened in the same manner. These drills were operated at spindle speeds of 675 RPM which is approximately 60 surface feet per minute. The feed was varied between .006" and .012" per revolution. At this time, we were using a sulphurized petroleum and fat oil with chlorine added; this combination gave excellent results. The oil pressure on the drill was approximately 280 in. pounds and there was very little heat generated.

(3) Correct Tap Design and Manufacture - Taps were designed and made in such a manner as to compensate as much as possible for the characteristics and properties of titanium. The steel selected for the taps, which we used in torque and endurance tests was 18-4-1 high speed steel partly because we would prefer to use this as a general purpose steel. The blanks were fluted, using a modified round flute form which produced a hook angle of 6 to 8° and a cutting angle of approximately 11 to 12°. These were highly polished; the thread was ground in a conventional manner. It produced a tap which had a full eccentric relief and a back taper of .001" per inch in length. A chamfer of 3 to 3 1/2 threads was used, and the point diameter equivalent to a minor diameter of 83 1/3% of thread. These taps were finally surface heat treated to impart extra skin hardness.

(4) Suitable Lubricant - In our search for a lubricant we enlisted the aid of an oil specialty house. With their help we went through a series of oils, from sulphurized petroleum oils to sulphurized petroleum and fat oils with chlorine added. This latter combination proved very effective as indicated in the torque test report. To give you a few facts from the torque test data sheet - the material was titanium base alloy Ti-150-A, in the annealed state. Its physical dimensions were 6" x 6" x 3/4". As annealed, it showed a tensile strength of 150,000 pounds per square inch. Drills were used which would produce 65% thread in the hole when tapped. These were high cobalt, high speed steel, and sharpened as previously described. The taps used were 3/8 24 National Fine, Commercial Ground. They had a point diameter of .328"; in all other respects, they were as previously described. Additional equipment included a strain gauge dynamometer, a Brush Universal Analyzer, a direct inking oscillograph and a radio drill press.

The following is a series of preliminary torque tests which were run using one lot of taps and varying the lubricant. The results obtained can be shown in a table arranged in the order of decrease and torque. The test is run with the taps working at approximately 20 surface feet per minute.

The first test was run without any lubrication. The average torque was 210 in. pounds. In the second test, a sulphurized petroleum and fat oil, cut with kerosene 1-1, with a sulphur content of 1 1/2% was used. The average torque was 140 in. pounds. In test 3, the lubricant was 3 1/2% sulphurized petroleum and fat oil; the average torque was 121 in. pounds. The next test, using sulphurized petroleum and fat oil with a 10% chlorine additive, produced an average torque of 107 in. pounds. In the following tests, a sulphurized petroleum and fat oil also produced an average torque of 107 in. pounds. For test 6, we again used the sulphurized petroleum and fat oil with molybdenum sulfide added; the average torque was 98 in. pounds. For test 7, a 3 1/2% sulphurized petroleum and fat oil with a trace of chlorine was used; the average torque was 97 in. pounds. For test 8, we increased the amount of chlorine; the average torque was reduced to 80 in. pounds. In test 9, we doubled the amount of chlorine; no corresponding change in torque was reflected. In test 10, we again used the 3 1/2% sulphurized petroleum and fat oil and quadrupled the amount of chlorine which was used in test 8. This produced an average torque of 47 in. pounds.

The minor diameter of the holes in this series of tests was for 65% of the thread, with a minor diameter of 75% of thread, and the oil used in test 10, the average torque values were in the order of 83 in. pounds. A good supply of lubricant was kept on the tap and in the hole during the entire tapping cycle. There was a considerable

amount of squealing during tapping and backing out except in the low torques. In the first five tests there was a tendency to seize and bind.

In addition to the torque tests endurance tests were run in one of our customer's plants on a part of the same lot of 3/8 24 National Fine taps. At spindle speeds of 225 RPM, approximately 20 surface feet per minute, and using sulphur concentrate, they averaged 200 holes per tap before the cutting edges broke down. We believe that further tests using 3 1/2% sulphurized petroleum and fat oils with chlorine added will increase tap life.

TURNING AND MILLING OF TITANIUM

By: NORMAN ZLATIN, Partner, Metcut Research Associates,
Cincinnati, Ohio

I would like to discuss some of the machining properties of the titanium alloys, particularly with respect to those of the replaced metals. Before discussing the tool life results obtained in turning, it would be well to describe the method of measuring tool life. With carbide tools, the wearland on the shank of the tool is measured with a Brinell microscope at intervals during the machining operation. When the wearland reaches .015", the end of tool life is assumed. Tool life values of this type are obtained over a range of cut speeds and a tool life curve can then be drawn from the results.

In turning the titanium alloy Ti-150-A with various grades of carbides the results were as shown. The 78 and 78B grades are usually used in the machining of steels. The straight tungsten carbide grades such as K6, 905, 883 and HA were the best. Using one of the grades in the group which proved best, tool life curves were obtained on the three more widely used titanium alloys, MST 3 Al. - 5 Cr., RC-13CB and Ti-150-A. With the K6 carbide the cutting speed for a tool life of 20 minutes was 100 ft./min. for MST 3 Al. - 5 Cr., 180 for RC-13CB and 200 for Ti-150-A. With high speed steel tools, the cutting speeds for a 20 minute tool life is relatively low - 30 ft./min. for RC-13CB and 45 for Ti-150-A. It is not practical to cut the MST 3 Al. - 5 Cr. alloy with high speed steel tools. An actual comparison was made of the machining properties of the titanium alloy Ti-150-A with those of several stainless steels. The tool life results reveal that the stainless grades AISI-430, 410 and 347 can be turned at cutting speeds 3 and 4 times that at which the titanium alloy can be cut.

Comparison for the machining properties of the titanium alloy and a steel of equivalent hardness show that for a given tool life, the quenched and tempered SAE-4340 steel can be machined almost twice as fast as the Ti-150-A alloy. These comparisons of the machining

properties of the titanium alloys with those of the aircraft metals now being used should indicate to prospective users of these new alloys some of the production problems they will face in turning. Use live centers.

The milling of titanium presents a challenge to the tool engineer. First, there is a tendency for the titanium to smear over the shank of the tool, thereby causing rapid tool failure. Hence the magnitude of the relief angle is particularly critical in milling titanium. The results of milling tests have indicated that there is less of a tendency for the titanium to smear over the shank of the tool with a 12° relief angle than with a 6° angle. However, if the relief angle is increased beyond 12° , the cutting edge is weakened and chips too easily. The second problem is aggravated by the very nature of the milling operation. The cutter cuts only part of each revolution. During the portion of the revolution that it does not cut, the titanium chip remains welded tightly to the cutter's edge. As the chip is knocked off at the start of the next machining portion of the revolution, the cutting edge of the tool usually chips away. Further breakdown of the tool is thus greatly accelerated.

There is less chipping of the cutting edge if light feeds are used, $.004''$ to $.008''$ /tooth. With carbides, a negative rake of 10° is recommended; while with cast alloys 0° to 6° positive is best. Carbide tools, because of their brittleness, are often not recommended for milling titanium. However, if the carbide tools are used with a cutting fluid, a cutting speed of 50 to 70 ft./min. will give a reasonable tool life. With cast alloy tools the cut speed is 40 to 50 ft./min.

FUNDAMENTAL FACTS ON MACHINING TITANIUM

By: DR. M. EUGENE MERCHANT, Assistant Director of Research,
Cincinnati Milling Machine Company,
Cincinnati, Ohio

There are two basic processes that go on in the cutting of metal by a cutting tool. There is a process of plastic flow of the metal ahead of the cutting tool to form the chip. If the tool moves through the metal, plastic flow takes place, shaping the chip. The second process is the escape of the chip over the face of the tool where it meets very high frictional resistance, and where it presses against the tool face with very high force. Both of these processes generate a great deal of heat. Heat, then, is also very important in determining what happens - particularly what happens to the cutting tool and how it will stand up - because heat causes tool failure. The hotter the tool, the more rapidly will it wear.

From studies made in our laboratory in this connection I am going to give you data which is mainly on Ti-150-A alloy, cutting with carbide

tools, mainly Grade 883 carbide, and over a range of feeds and speeds. Measurements were made under these conditions to find out what was going on in the processes of plastic deformation and in the rubbing friction between the chip and tool. Comparisons were made between the Ti-150-A alloy, and a 1020 steel - one of the simplest types of steel - just to see to what extent there were differences, and to what extent there were similarities in machining processes.

First of all, the plastic deformation process was considered, and it was found that very much less plastic deformation occurred ahead of the tool in forming the chip when machining titanium than when machining the steel. In fact, the plastic deformation taking place was less than half as great when machining titanium as when machining the 1020 steel. That meant that a great deal less heat was generated when machining titanium, from the source of plastic deformation. Now this plastic deformation is controlled by two or three main factors, one of which is the amount of friction between the chip and tool - the factor that I called the second basic process. That has an effect on the amount of heat coming from that deformation. When friction between chip and tool is low, the plastic deformation is also considerably reduced ahead of the tool. Secondly, the amount of plastic deformation is a function of the property of the material itself, and of its mechanical properties, and titanium happens to have such properties that it also gives less plastic deformation for a given amount of friction between chip and tool than does steel. So it was found that if we did happen to have the same friction between chip and tool with steel as with titanium, we would still get a lot less deformation of the metal with titanium because it has built into it unusual mechanical properties; it is the nature of the metal itself to give less plastic deformation. These factors, so far, are all to the good.

What about the friction between the chip and tool itself? Well, comparing values of friction obtained with titanium 150-A and 1020 steel taking a cutting speed of 150 feet per minute and a feed of about .005" there is noticeably less friction between chip and tool when machining titanium than when machining steel. The value of the coefficient of friction for 1020 steel was about 0.9; for titanium about 0.65 - less friction than, in general between chip and tool, along with less plastic deformation of the metal. Here, again, is a good characteristic.

What about the resistance of the metal to the stress required to produce plastic deformation? How does that compare for the two materials? Taking the 1020 steel and the Ti-150-A alloy, it was found that the stress required to produce plastic deformation in forming the chip was about the same for both of them -- something on the order of 50,000 pounds per square inch. These factors taken together all result in the good chip formation which I have mentioned, in the good figures for power consumption, and in the good finish. The power consumption

is going to be less with titanium than with the 1020 steel because of the good values of these factors already mentioned - about 25 to 30% less - under a given set of conditions, even though the titanium is a much stronger metal. This lower power consumption is due to the somewhat lower chip friction and considerably lower plastic deformation that occurs in forming the chip. The chip formation is good because of the fact that there is this small amount of plastic deformation which I mentioned. The metal is not severely deformed in producing the chip, and so the chip rolls off very nicely. This is also tied in with the matter of surface finish.

Surface finish is influenced by the presence of what is known as built-up edge. If the metal being machined tends to adhere to the face of the tool and build up a stationary mass of metal on the nose of the tool, that is known as a built-up edge. When this exists, fragments of that built-up edge continuously go off with the finished surface and leave little steps or fragments attached to that surface which cause it to be rough. With steel such as 1020, you get a noticeable built-up edge under many machining conditions; however, it is significant that when machining titanium, you seldom get a built-up edge; that there is not this same tendency in general for the metal of the chip to adhere to the tool face to build up and cause this stagnant nose on the tool which roughens up the surface. This is due in part to the lowered friction between the chip and tool obtained with titanium; it is due in part to the fact that less plastic deformation takes place in forming the chips, because the formation of the built-up edge is associated with that also. It is probably also due in part to another factor which we will shortly mention.

Nothing we have said would seem to indicate why we should get poor tool life, but as we look further into this chip formation process and what happens in cutting, we begin to see some problems peculiar to titanium. For one thing, there is the question of bearing pressure between the chip and tool. The chip is being pressed against the tool with considerable force; if over a fairly large area, things will not be serious; if over a very small area, problems arise. With investigation, we find there is a big difference in the size of the bearing area between the chip and tool when machining titanium and steel. On machining Ti-150-A with a 883 carbide at a speed of about 150' a minute, .006 feed per revolution, on titanium, the area of contact between chip and tool was about .006 of a sq. in.; on steel, nearly .010 of a sq. in.; therefore, on machining titanium the bearing area is much more highly loaded.

Of course, the bearing area between chip and tool is one of the most highly loaded bearing areas in commercial practice today, and when you go cutting down that bearing area by half you can see you are getting into some severe problems. That is part of the reason why titanium wears the tool so rapidly -- because of these extreme bearing pressures between chip and tool. This same bearing area, however, has

another detrimental effect, in that it concentrates all the frictional heat developed by the sliding of the chip on the tool on a much smaller area, and therefore, results in a considerably higher tool temperature at that area; furthermore, titanium has relatively poor heat conductivity. All of these factors taken together - the small bearing area with the very high bearing pressure and the poor heat conductivity of the metal - lead to extremely high tool temperatures and extremely high temperatures on the bearing area where the chip rubs on the tool. Taking again some typical data: 883 carbide machining at 150' a minute, .006 feed per revolution, the temperature on the bearing area when cutting 1020 steel was about 600°v; when machining titanium it was about 2250°F -- a tremendous difference. So you can begin to see why the tool seems to practically melt away under some conditions when machining titanium.

One factor entering the picture is the solubility of titanium in and with practically all known metallic materials and refractory materials, too, for that matter. Because the tool metal is so soluble in and with titanium, it tends to dissolve in the titanium chip at the bearing area. That is, as the chip is racing over the face of the tool at these high temperatures, an alloy is actually being formed between the titanium and the tool material because of its easy alloying properties. That alloy, of course, is then carried off with the chip and produces tool wear by depleting the tool metal.

This alloying action has other significant consequences. You may be acquainted with the fact that, in machining titanium, if for some reason you slow the cutting speed down to a very, very low value, or even stop the tool in the cut, when you start again a built-up edge will form and finish will be poor, and there will be considerable building up of the titanium on the tool face. This can also be attributed to this alloying action because when the cut nearly stops, with the chip in contact with the tooth and the temperature drops, then the chip freezes to the tool face because of this alloy which has been formed between the two. When you start up again, the chip sticks to the tool face and leaves a layer of titanium on it which is the beginning of a built-up edge. This effect, which has sometimes been attributed to work hardening, is merely a matter of the alloying action between chip and tool and, of course, can be prevented by not allowing this alloy to set. This is also the cause of difficulties in milling. The chips tend to stick to the milling cutter face, and go around with the cutter. As the tooth leaves the cut, the chip freezes to the tool face, and when bumped off the next time, the tooth enters the cut; it fractures a little bit of the tool material away; it chips the tooth.

These, then, are some of the basic reasons why titanium machines as it does. An understanding of these and other basic facts about machining of titanium hold the key to solving the manufacturing difficulties and improving the manufacturing processes involved in the actual machining of titanium.

TITANIUM AS A NEW PRODUCTS POTENTIAL

By: FRANCIS G. TATNALL, Director of Testing Research, Baldwin-Lima-Hamilton Corporation, Philadelphia, Pennsylvania

I am old enough to have been around at the debut of various other glamorous materials. I have seen the high and low alloy steels come in. People promised great things for them. Finally, after much developmental work they became very fine, useful materials. I've also seen aluminum come in and settle down as an indispensable product.

Now we've got another one - Titanium. Titanium is strong as steel. Titanium has corrosion resistance. That is what we hoped to get in our low alloy steels, you know. Titanium is low in weight. Titanium has high temperature properties. Excellent - but titanium has low stiffness values and low stiffness is not good.

In order to speak about any metal it is necessary to refer to the stress-strain diagram. The elastic line, the plastic range, the ultimate strength and the breaking strength are the various things which should be known about any material. The cold working ability of the material is very important. You want to work harden if you are going to draw wire, or if you are going to do various kinds of work to improve its properties by cold work. But titanium apparently cold works so fast that the slope of the stress-strain curve is probably very steep.

Toughness of the material is the ability to absorb energy. In armor plate you want to absorb energy. The ultimate strength is the hardness in the material. That's the equivalent of the hardness we're talking about. If we have adequate stiffness you can always say its better than aluminum. We are not concerned with comparing titanium to steel.

In corrosion resistance we find that it is better than steel, and in some cases, better than stainless steel. I think they said here today that titanium stays stainless, whether you keep the heat on or not.

Do we have good resilience? You don't want it to bend, because when it bends especially if you work harden it a little bit, and you take the load off, you've got a permanent set. When you've got a permanent set, the people will send your product back to you. Its the elastic range that gives you the toughness.

The main property of anything is notch sensitivity. If you strike a piece of titanium with a hammer, will it bend or break; will it take a lot of foot pounds of energy, or will it take a few? That brings up two things: the difference between cleavage and shear. Shear requires

work to break it. If you've got shear, you've got to do more work before it breaks, but if you have cleavage the metal will break suddenly, without any extra work at all. If that stress concentration is relieved by plastic flow at the root of the notch the metal is not notch sensitive, and it will probably fail by shear, which is a very delightful way - but if it is notch sensitive, it will fail suddenly, and with very little deformation, and that is another thing that makes people send your products back to you.

Most of you would like to make titanium castings. We make ship propellers, and the first thing we want to know is can you get enough titanium to make a propeller? Are the advantages: lightweight, corrosive-resistance, and cavitation contained in titanium? If we can make propellers, why can't we make tail shafts out of it, and then we would get the marine industry fixed up, as these are the only two things that bother the marine industry.

I see they're alloying titanium with copper, with chromium and with things that have vastly different possibilities. I was told, by a very respectable metallurgist, that we can change that modulus from 15 million to 24 million, depending upon the alloy we used. I think you will find in five years people will say that was wrong.

If we can alloy titanium and can do almost anything with it, then we haven't scratched the surface yet. Maybe I can make wire for our bonded wire resistant strain gauges out of it which will have a wire gauge factor and would be worth a million dollars to anybody.

The transition temperature is something that most things have. A ductile material will become brittle at some particular temperature. It can be as ductile as anything at room temperature, and when you take it outside in the normal Boston atmosphere it will suddenly become brittle. What we are continually trying to do is to lower that transition temperature, because we don't want to say a thing is ductile when it is brittle. In other words, shear changes to cleavage, due to reasons about the space lattice.

What happens to material when it is heated up? First, its modulus goes down as heat goes up, until when the thing is liquid it has no modulus at all, because you can bend a piece of liquid metal. Titanium behaves very well at low temperatures, whereas the only thing that's behaved well in the past has been nickel. Now, incidentally, they are alloying titanium with nickel. If we can replace the nickel in this material, then we can use titanium, and then we've got invar. Invar is a lovely material which is pretty nearly stable at a wide range of temperatures so that you can use it in all kinds of gauges and things which will not expand or contract, or change their modulus as temperatures change. We couldn't make our testing machine if we didn't have something of the invar type of material. If somebody will develop a

titanium invar there is quite a field for that. Someone should also develop a wire with a very, very high gauge factor, i.e., the change in resistance divided by the original resistance times the strain.

Creep is holding a metal at constant load over a period of time and measuring the strain. If strain takes place, the thing will just creep and the metal just stretches under this constant load. If you could cause it to stretch less and less, with more and more load, you have a good material. Does titanium do this? If it does, we have many uses for it in gas turbines, high temperature materials, in oil refineries, steam boilers and wherever high temperatures are as famous as they are now. Is titanium a metal? The higher the modulus, the more metallic the material gets. Magnesium is just barely a metal; aluminum is a little bit nearer a metal. Plastics, of course, aren't a metal. Steel is definitely metal. Relaxation is the reverse of creep. If you are going to make flange bolts, relaxation is plotting stress with constant strain. In other words, when you bolt up a flange with a gasket in it, if the bolt stretches, the strain is constant, but the stress falls off with the load on those bolts, and the gasket starts to leak. If we have good relaxation properties in titanium - which nobody has told me of yet - we have two very fine things. One is that we will have good annealing properties because annealing of materials is nothing but relaxation between high points of stress locked up in a material and thus we would have good bolting up in flanges and things of that kind in our oil refineries, chemical plants, steam plants, et cetera.

Where is the endurance limit? It changes all the time with those various things. If I put that notch in, it changes like anything. What is damping capacity? Cast iron has high damping capacity. That cuts down the danger of failure by fatigue in a structure and that's this: damping capacity is hysteresis in a reverse cycle. It turns vibration into heat; it is much better to have a thing turn into heat than to fail by vibration. I would like to know what the damping capacity is; I imagine it's high.

Somebody mentioned sensitivity to high straining rate. You've got to push this slowly; some metals are sensitive to high straining rate and won't develop loads. Austenitic stainless steel has a beautiful stress-strain diagram; it ought to absorb any energy like shooting a bullet into a piece of armor plate made of stainless steel. If you shoot fast enough, the bullet goes right through like butter; if you shoot slow, you can't push it through anything.

Heat conductivity. How fast will heat pass from side to side and not set up a tremendous thermal shock. Crack propagation is very good in titanium. What about strain aging? What happens after you strain it and let it sit out a little while? Does it change?

Sensitivity to surface damage; magneto-striction. Suppose nickel has high magneto-striction. If this is going to be a substitute for nickel, it might require high magneto-striction. Does it have a blue brittle range? Does it get brittle at 400°? Does it have a temperature of embrittlement at 900° like steel? If it does not you've got a product that's better than steel. What are we going to use this for? Here are the uses: pressure vessels, tubes, flanges, cold drawn heads.

What can we do with pressure vessels? How about inner shells or liners for pressure vessels? How about containers? How about valves in chemical service? Aeronautics? Automotives? Just think of engines of lightweight, corrosion-resistant, higher temperatures? How about ships, the railroad business, chemical ware, kitchen utensils, laboratory apparatus? Does it replace aluminum, magnesium, stainless steel? How about the spot welding? Can we get into the medical field? Do you know what they put into people when they splice bones, use pins and all those prosthetics?

What can your civil engineer use it for? For structures - especially the structures around the sewage disposal plant - places where there is corrosion. At the same time, it is lightweight and the mechanical engineer could use it in his power equipment; the petroleum engineer; the architect!

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