# Metallurgy In Orthodontics

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For the correct use of orthodontic appliances one must have a thorough knowledge of the materials from which these appliances are made. The mechanical and physical properties of these materials change greatly under varying conditions of manipulation. The light, continuous pressures produced by these appliances stimulate osseous development in the direction desired. Thus they have a dynamic nature, producing sufficient pressure to stimulate movement but not enough to cause necrosis of the bony tissue. The appliance must act within maximum and minimum limits; therefore, its capabilities for applying force should be known. Since the physical properties of these materials are manifestations of their molecular nature, a discussion of their fundamental atomic structure is in order.

## Molecular Structure

In the solid state the arrangement of the atoms determines to a large extent the physical properties of that solid. If the atoms are arranged in a regular pattern, the material is said to be crystalline. The regular atomic arrangement in crystalline materials usually conforms to one of three basic geometric forms within the cubic system.[1] These forms are described as simple cubic, face-centered cubic and body-centered cubic. Most of the metals used in orthodontics are either face-centered or body-centered. The body-centered lattice is a cube with an atom at each corner and one in the center. The face-centered cube has an atom at each corner and one in the center of each face instead of a single atom

in the middle of the cube. Crystals large enough to be seen in the microscope contain millions of atoms arranged in one of these cubic forms and built up, one cube upon another. Spare electrons in the crystal are not bound to any one particular atom but are free to move about thus giving the metal the ability to conduct heat.

Orthodontic wires are made from high density castings. When the molten casting solidifies, minute impurities which exist act as centers of crystallization. At these centers space lattices begin to attach themselves to each other. These form outward growths or dendrites which continue to grow until they meet other forming nuclei. The solid mass formed from each center of crystallization is called a crystal grain. The number of grains formed depends upon the number of original nuclei of crystallization which formed. The faster the casting is cooled, the greater will be the number of nuclei formed and, therefore, the smaller will be the grain size.

The shape of the grain may be changed by applying a force to the material. Because the grain is made of atoms arranged in the form of cubes and held in place by mutual attractions and repulsions, there are planes in this arrangement along which there is less resistance to movement than along other planes. When stress is first applied, the space lattice is slightly distorted out of shape but returns to its original position upon release of the stress. This deformation is called elastic strain. The maximum stress to which the material may be subjected without any permanent deformation

remaining upon release of the stress is called the elastic limit. If the stress is greater than the lattice can bear elastically, permanent deformation takes place and one series of atoms moves along another series of atoms. The plane along which this movement takes place is called a slip-plane. The size of the grain and the number of slip-planes present in the individual grain determine the amount of plastic deformation which can take place. The slip-planes usually do not extend entirely to the grain boundaries indicating that the grain boundaries are stronger than the material at the interior of the grain. This is probably due to a greater distortion in the shape of the space lattice at the grain boundary. This distortion causes internal friction making slip more difficult. For this reason fine-grained alloys are preferred, the more grain boundaries present, the stronger the material; also, the smaller the grain size, the greater the tensile strength and elasticity.

Grain size can be reduced by alternate plastic deformation and recrystallization. In the fabrication of wires the cast metal or ingot is rolled or drawn down to size in stages. Between each stage the wire is heated to the recrystallization temperature of the metal, thus producing smaller equiaxed grains. The drawing process elongates the grains into long fibrous structures, the long axes of the fibres running in the direction of drawing. This mechanical adaptation or deformation of the metal is known as cold-working and the finished product is described as a wrought structure. The characteristic properties of wrought structures are very different from those of cast structures both in microscopic appearance and physical properties.

### PHYSICAL PROPERTIES

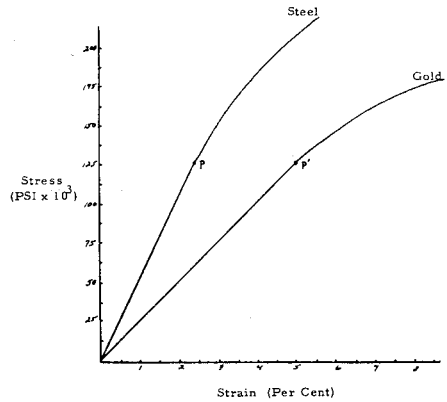The orthodontist is mainly interested



Fig. 1 Typical stress-strain curve for stainless steel and gold wires. Graph based on manufacturers' physical property charts.

in only a few of the physical properties of the appliance. The more important of these are the modulus of elasticity, proportional limit, modulus of resilience, and tensile strength. The modulus of elasticity, a measure of the stiffness of a metal, is the ratio of stress, within proportional limit, to corresponding strain. This is illustrated in the graph in Figure 1 showing the typical relationship between stress and resulting strain for both gold and steel wire. The strain will remain directly proportional to the stress and no permanent strain will remain after the stress is removed as long as the values P or P' are not exceeded. If these values, which represent the proportional limits for the corresponding alloys, are exceeded, some degree of permanent deformation will remain in the wire after removal of the stress. The rigidity of either alloy can be determined by the slope of the corresponding line which represents the modulus of elasticity. It can be seen that the modulus of elasticity for steel is almost twice that of the wrought gold wire. Since a high modulus of elasticity is coincident with lowered resilience, a gold wire is ap-

proximately twice as resilient as a steel wire of the same size. The modulus of resilience, which is the work required to stress one unit volume of a material to its proportional limit, can be determined mathematically by the formula $R = P^2/2E$, where P signifies the proportional limit and E is the modulus of elasticity. It can be seen from this equation that the proportional limit is the main factor governing the modulus of resilience of a wire since its value is squared. A wrought gold wire will bend twice as far as a steel wire of the same size when subjected to equal forces within the proportional limit. Clinically, this means that a tooth will be moved twice as far with a wrought gold spring as it will with a steel spring of the same size wire under equal initial forces. In order to accomplish the same amount of movement of the tooth, the steel spring would need more frequent adjustment. The high elastic modulus of steel can be compensated for by using wires of smaller dimensions where larger deflections are required.

In order to form an archwire with various loops and springs, the wire must possess the ability to be deformed plastically without fracturing. This property is known as ductility. If the ductility of the wire is too low it will fracture on bending. If the ductility is too high, applied forces will quickly cause the archwire to lose its shape because of lowered elastic qualities. Wrought gold alloys work harden much more slowly and to a lesser degree than steel, thereby allowing a greater degree of manipulation.

As mentioned above, the proportional limit designates the maximum stress at which strain remains directly proportional to stress. It determines the force which is required to put a permanent bend in the wire. It is dependent upon the chemical composition of the wire, the heat treatment, and the amount of cold work to which the wire has been subjected. All forces above the proportional limit result in the wire acquiring a permanent set. If the force is increased still further, a point is reached where the wire will break. This maximum force or stress is known as the tensile strength. Fracture of the wire occurs when the internal stresses in the wire resulting from the applied forces reach a degree which can no longer be resisted by the inherent strength of the metal. Very high stresses can be applied if they are uniformly distributed along the wire. When severe bends are placed in an archwire, localized concentrations of stress are produced which can result in fracture if these stresses are not relieved by heat treatment. Any pits or cracks in the wire can cause a very localized concentration of stress resulting in extreme plastic deformation and fracture.

Orthodontic appliances are subject to repeated small stresses which can cause metal fatigue. Fatigue is a process which leads to fracture under repeated or fluctuating stresses which have a maximum value less than the tensile strength of the metal. The fatigue life of a metal is governed by many factors including microstructure, surface condition, and corrosion resistance. The incidence of fatigue failure is also increased by the presence of very small surface defects such as pits or cracks. In many cases corrosion causes mircoscopic pitting which greatly shortens the fatigue life of the appliance. Both the size and shape of the grains also influence this process since fatigue failure develops from minute cracks which grow through the grain. Because the grain boundaries are stronger than the interior of the grain, the greater number of boundaries present in a fine-grained wire will increase

the resistance to fracture. Although of great importance, fatigue data as supplied by manufacturers of gold and steel alloys is very limited.

## TYPES OF STAINLESS STEELS

The term stainless steel is applied to all alloys of iron and carbon which contain chromium, nickel, or other elements which impart to the steel the property of resisting corrosion. There are over forty stainless steel alloys whose properties vary greatly. The three main groups are martensitic, ferritic, and austenitic. The steels used in orthodontics come from the austenitic group. The most widely used 18/8 alloy contains approximately 18 percent chromium, 8 percent nickel, 0.2 percent carbon, and a trace of stabilizing elements. All of the austenitic steels have good corrosion resistance, hardness, yield and tensile strength. However, small sizes of wire usually demonstrate these qualities with quite a large degree of variation. Austenitic steels are nonmagnetic unless heavily cold-worked, which results in slight magnetism.

Metallurgists do not agree on the reason the stainless steels resist corrosion. It is generally believed that this resistance is due to the presence of a hydrous oxide film which is stabilized by chromium. This film forms naturally on the surface of the wire upon exposure to a suitably oxidizing environment.[2] The film, which varies in composition from alloy to alloy, cannot be seen microscopically, is transparent and insoluble. If its continuity is broken by welding, soldering, or mechanical working, it will reform naturally within a short period of time. Its formation may be hastened by exposure to a strong oxidizing agent. If the metal is to be exposed immediately to saliva, the continuity of the film can be restored by a process called passivation.[3] This is an electrolytic process similar to electro-plating except that the anode and cathode are reversed. The appliance itself acts as the anode. When the passivator is activated, a microscopic layer of metal is removed as the anode ionizes into the acid bath. This produces a high polish and restores the film changing the previous chemically active surface into a much less reactive state. As with many other alloys, the stainless steels may have a lowered resistance to corrosion after cold work.

## SPOT WELDING

Spot welding is the fusing together of two metals through the induction of intense heat. Chrome alloy is especially suitable to resistance welding since its electrical resistance is high and its thermal conductivity low, resulting in a restriction of the flow of heat to the immediate weld area. The heat is internal, being generated at the point of contact by the resistance of the parts to be joined to the passage of a current of high amperage. The metals melt at the point of contact. Upon cooling, there is a recrystallization across the interface, thereby joining the two parts. In pulsation welding several spots of liquefaction and recrystallization are made during one complete cycle of the welding machine.

The metals must be in contact at the spot to be welded or else the heat will be lost over too wide an area giving a poor weld. When the metal is heated it tends to expand. All of the austenitic grades of stainless steel have high coefficients of thermal expansion. If too intense a current is used, the metals heat and expand too rapidly. This results in small particles being thrown away from the weld. This sparking, which is also caused by lack of ample pressure between the electrodes, produces small surface irregularities and voids in the metal which tend to weaken the structure, sometimes to a marked
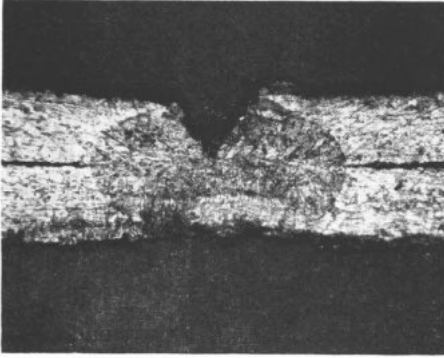
Fig. 2 Improper weld between .003 band material strips. The large void was caused by sparking, the result of too intense a current. X 200

degree. These voids and surface markings may be seen in Figure 2 which shows the welding together of strips of .003 stainless steel band material. Too large a current also results in complete fusing of the metals between the electrodes, and the pressure applied produces a very thin section. This may be seen in Figure 3 which shows the flanges of a bracket welded to .003 band material. Excessive current and pressure resulted in extreme thinning of the band material on the right side of the photomicrograph, while a stronger weld is shown on the left. Since the unchanged metal is stronger than
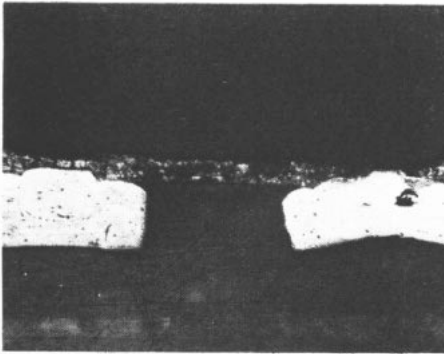


Fig. 3 Bracket flanges welded to a stainless steel band. A proper weld is shown on the left. X 100
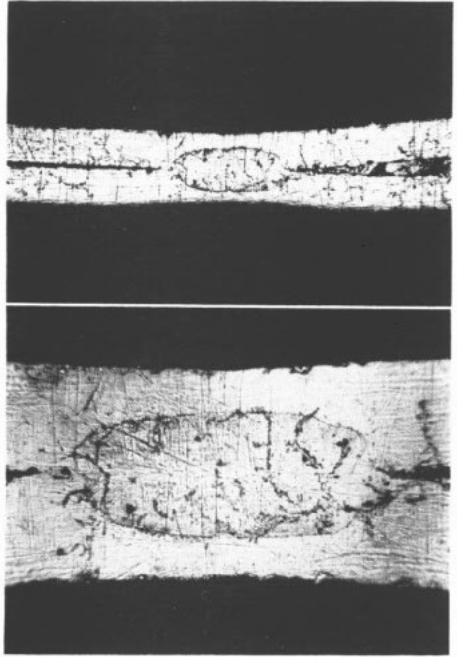


Fig. 4 Above, A proper weld between strips of .003 band material. X 200

Below, Enlarged view of the weld seen above.

the recrystallized weld area itself, a certain amount of the original structure should remain on each side of the weld.

A proper weld is one in which the weld area itself covers approximately the middle one-half of the cross-sectional diameter of the two parts being joined. This may be seen in Figure 4 - above showing a weld between strips of band material. This type of weld imparts maximum strength to the structure. A closer view of this weld may be seen in Figure 4-below. Notice that there are few surface irregularities present. If the proper current, pressure, time interval, and electrodes are used, there will be little or no marking on the surface of the metals after welding.

In the welding of stainless steels there is always the possibility of initiating corrosion. The chemical reaction of

chromium with carbon and oxygen can occur at welding temperatures.[4] This may produce oxidation of the bonding surfaces. In order that the metal remain metallographically unchanged, it should be heated very quickly at the point of contact and then cooled quickly. Welding produces a temperature in the surrounding area of the weld which is within the carbide precipitation range of approximately 800-1600° F. The exact temperature depends upon the carbon content of the alloy. This accounts for the constant danger of chromium carbide precipitation even with the stabilized alloys which will be discussed shortly. At these temperatures the carbon atoms acquire sufficient energy to diffuse together and precipitate from solution. Figure 5 is an electron micrograph of a replica taken from the surface of a stainless steel wire which was heated at 1000° F. for 30 seconds. The small white dots which can be seen scattered throughout the micrograph represent individual chromium carbide particles. The chromium carbide is precipitated mainly at the grain boundaries at these high temperatures. The passivating qualities of the chromium are lost when it combines with the
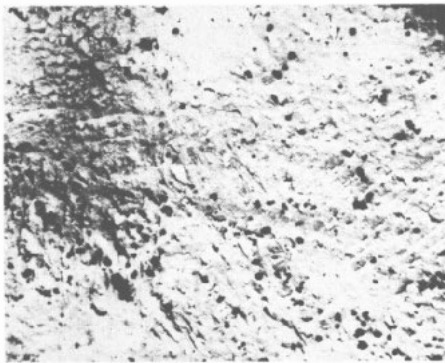


Fig. 5 Electron micrograph of a replica taken from stainless steel. The steel was heated for 30 seconds at 1000° F. The small white dots represent chromium carbide particles. X 14,000

carbide, thus promoting susceptibility to corrosive attack. Partial disintegration of the metal may result in a corrosive environment such as the oral cavity. Since the chromium is removed mainly from the boundaries of the grain, intergranular corrosion is usually initiated. Although decreasing the carbon content decreases the susceptibility of the steel to intergranular attack, this is not commercially feasible. The addition of titanium or columbium to 18/8 low carbon steel results in these elements being precipitated as carbides in preference to chromium. Stainless steels which have been treated in this manner are referred to as "stabilized". This inhibition of chromium carbide precipitation takes place for only a very short period of time at the temperatures encountered in welding and soldering. Unfortunately, many of the stainless steel alloys which are used in orthodontics are not stabilized.

Besides carbon content, the length of time which the metal is held at the sensitizing temperature is important. Precipitation of the carbides at the grain boundaries takes place very rapidly. Although the time of current flow is approximately one-fiftieth of a second, the metal adjacent to the weld may become subject to intergranular attack; the weld metal itself and the metal outside the heat-affected zone may remain virtually free from attack during this time interval. This is due to the fact that at the center of the spot weld the metal is heated to a temperature above 1600° F. At these high temperatures the chromium carbide breaks up into its component elements. This may be seen in Figure 6 showing a steel specimen heated at 1900° F. for 30 seconds. There is a complete lack of carbide particles, although the high temperatures have caused a growth of subgrains. However, surrounding each weld is a ring
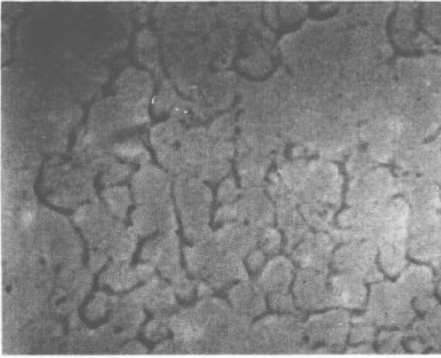
Fig. 6 Electron micrograph of a replica taken from a stainless steel wire heated at 1900° F. for 30 seconds. No carbide particles are present. Note the growth of subgrains.   X 26,000

of metal which has been heated at a slower rate through the range at which carbide precipitation takes place. It is here that the chromium is removed from the grain boundaries. This structural alteration is responsible for the discoloration, corrosion, and failure of welded joints which are seen in clinical use.

HEAT TREATMENT OF STAINLESS STEEL

Stainless steel, because of its constitution, can be strengthened only by cold-working or plastic deformation. Thus in forming an archwire, a very high tensile strength may be produced but its flexibility usually decreases in varying degrees. This is of importance since the elastic strength is one of the factors governing resilience of the wire. These properties allow the storage of forces and their delivery to the teeth at various rates. In order to increase the resiliency of the wire, various methods of heat treatment have been proposed. Kemler found that a low-temperature heat treatment caused an increase in the proportional limit and modulus of resilience of chrome alloy wires.[5] He found that an optimum heat treatment was five to fifteen minutes at

700-800° F. Backofen and Gales stated that ten minutes at 750-820° F. produced optimum results.[6] Funk produced the most marked increase in elastic properties at 850° F. for a period of three minutes.[7] However, he stated that good results can be obtained within a temperature latitude of approximately 200° F. In each of these methods a marked increase of as much as 40 per cent was produced in the resiliency, with corresponding improvements in the tensile strength and proportional limit. Although wires of smaller diameter absorb heat faster than wires of larger diameter, there is no significant difference in the results to warrant a time-temperature ratio for the various size wires.

Although heat treatments increase the elastic strength and resiliency of a wire, they produce only slight changes in the elastic modulus. In other words, the treatments change the degree to which the metal may be deformed, but the force for a given deformation remains almost identical. An archwire which has its elastic qualities increased by heat treatment will be more likely to assume its original shape after distortion. Since it will have more resistance to permanent set after deflection than a wire which has not been heat treated, maximum force will be applied during the expected range of tooth movement. Stabilization and anchorage will be enhanced because the archwire will maintain its form over a longer period of time. Opening and closing loops will produce a more continuous force over a larger range of tooth movement.

In conjunction with improving the elastic qualities of a stainless steel wire, the heat treatment relieves the stresses which are retained from cold-working. After work-hardening any spring temper chrome alloy, there is a tendency for the wire to return to its original

position. These internal stresses are usually unequally distributed throughout the wire after bending. Proper heat treatment will relieve these stresses sufficiently to cause a reduction in the amount of breakage seen in clinical use. When a force is applied to the archwire or spring, the total amount of stress present is equal to the residual stresses plus those produced by the force. If there is a great deal of residual stress present in the wire, plastic deformation may occur when only a small force is applied. If these residual stresses are removed, a greater force can be applied and a larger range of action will be present.

The degree of stress relief increases with increasing temperature. However, care must be taken not to approach the lower limits of the annealing range of the steel. This range commences at approximately 1100° F. If the wires are subjected to temperatures above 1100° F. for even short periods of time, some degree of softening will occur along with reduction in the proportional limit and tensile strength. If softening of a stainless steel archwire occurs, heat treatment procedures now in use are incapable of restoring its physical properties. The only way in which an annealed austenitic steel wire may be strengthened is through cold-working.

When the wire becomes annealed due to overheating, recrystallization of the metal takes place. The long fibrous grains which were produced by rolling and drawing in the fabrication of the wire are transformed into large equiaxed grains. These large grains, all of which have approximately the same dimensions in all directions, are responsible for the softened state of the wire. This process is governed mainly by two factors, time and temperature. A faster rate of recrystallization occurs at higher temperatures. Once this has

taken place, continued heating causes grain growth. The grain size can be reduced by alternate plastic deformation and recrystallization, care being taken not to prolong the heating.

If annealing is desired to relieve brittleness by producing a softened, more ductile wire, it can be brought about quickly by placing the material in an oven at a temperature of 2000° F. or by heating in a flame or with electrodes until red hot. The wire can then be easily manipulated; work-hardening will restore its temper.

In general, a more effective working appliance will be produced by the proper heat treatment. This procedure should be carried out only after the completion of all the necessary bends. Repeated checking of the effectiveness of the selected heat treatment procedure may be necessary at intervals since there is not as yet as satisfactory a level of quality control in the fabrication of stainless steel wire as has been attained in the manufacture of wrought gold wires. The effectiveness of the heat treatment is determined to a large extent by the composition of the steel. In many cases the exact chemical composition of the wire is not given and the physical properties are not clearly defined by the manufacturer. This, coupled with the quality variation seen in many chrome steel wires, makes the determination of a single heat treatment procedure for all situations virtually impossible.

### SOLDERING OF STAINLESS STEEL

The soldering of stainless steel usually involves a different principle of adhesion from that of gold soldering. In most cases there is no fusion between the solder and the steel as there is in precious metal soldering with gold. Instead, the union which occurs is usually a mechanical one. Microscopic examination of the interface be-
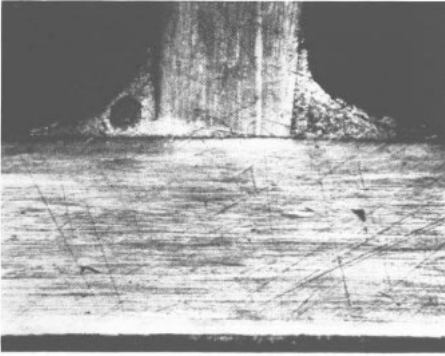
Fig. 7 Soldered union between two stainless steel wires. Void on the left is due to gas inclusion. Note the sharp line of demarcation between solder and steel. X 200
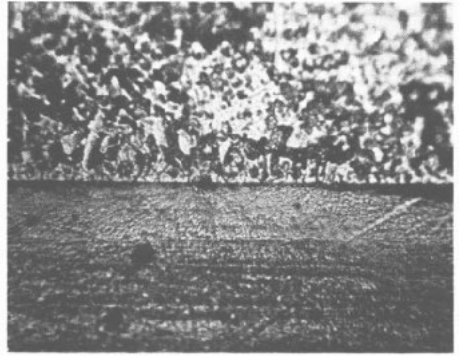


Fig. 9 Union between solder and stainless steel at slightly higher than normal temperatures. Slight degree of solder penetration is represented by the black line at the interface. X 500

tween the steel and solder usually reveals a clearly defined junction. Figure 7 shows a soldered union between two stainless steel wires. The line of demarcation between the alloy and solder may easily be seen. Figure 8 shows a wrought gold finger spring soldered to a stainless steel archwire. Note the greater degree of solder penetration which takes place with the gold alloy than that which occurs with the steel. The black line separating the solder from the alloy represents the area of solder diffusion or interalloying. How-
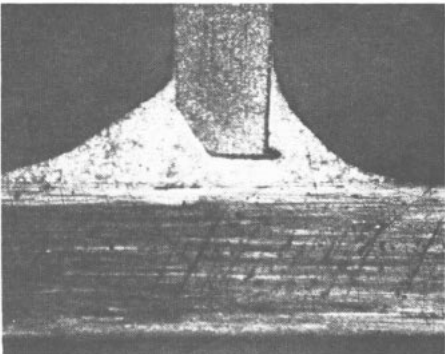


Fig. 8 Soldered union between a wrought gold finger spring and a stainless steel archwire. Note the greater degree of solder diffusion with the gold wire than that which occurs with the steel. X 200

ever, when higher than normal temperatures are used or the time interval in soldering is prolonged, a slight degree of interalloying with evidence of solder penetration into the steel can be demonstrated microscopically. This may be seen in Figure 9 which shows the union between solder and steel alloy at slightly higher temperatures.

As previously mentioned, it is important that the stainless steel wire not be heated to very high temperatures in order to minimize the danger of carbide precipitation and annealing. Since the degree of chromium carbide reaction increases with time, the steel should be quenched immediately after soldering in order to lower the temperature as quickly as possible. Steel wire should also be quenched after annealing. This rapid cooling prevents the formation of the chromium carbide particles which were broken up due to the annealing temperatures.

The melting point of the solder employed should be below 1100° F. In order for a gold solder to be sufficiently low melting, it must have a fineness of approximately 250. Many silver solders have slightly lower melting temperatures than most gold solders thus

reducing the hazard of overheating during soldering. In addition, the union between stainless steel and silver solder may be stronger than when gold solder is used.[8] If failure of this union occurs, it is usually the failure of the bond itself; the solder maintains its integrity when it separates from the steel. For this reason one must make sure that the solder wraps around the wires in order to impart sufficient strength to the joint. This is in contrast to the failure of the soldered union between precious metals which usually occurs adjacent to the bond due to structural failure of the wire.

The passivating film due to chromium makes it difficult for the solder to wet the surface of stainless steel during soldering. The flux which is used must contain a fluoride which will attack and remove this film. Other ingredients include sodium silicate, boric acid, and borax glass. A petroleum base is usually avoided because it may cause carbide formation on fusing.

A needle-like flame should be used since this will lessen the danger of annealing the wire surrounding the joint. This damage is also decreased by virtue of the low thermal conductivity of stainless steel. The control of temperature is even more important in the soldering of chrome alloy than in soldering precious metal. Care should be exercised to keep temperatures as low as possible and for as short a time as possible. When soldering fine wires such as finger springs or intermaxillary hooks, the softened part of the wire near the joint should be wrapped several times around the archwire to lessen the degree of breakage. Carbon-tip soldering is an improved method in which there is less danger of annealing. In this technique a current of sufficiently high amperage causes heating of the wire through which it passes. The solder and flux are fused onto the wire with fewer defects and in less time than when a flame is used.

### CHROME-COBALT ALLOY

Orthodontic wires composed primarily of a chrome-cobalt alloy are also available. The usual composition of this alloy is 40% cobalt, 20% chromium, 15% nickel, 7% molybdenum, 2% manganese, 0.15% carbon, 0.04% beryllium, and approximately 15% iron. Although similar to 18/8 stainless steel in most of its properties, the chrome-cobalt alloy differs in that heat treatment produces a greater change in resiliency than that produced in steel. This alloy also has a higher resistance to corrosion and fatigue than most stainless steels. Since it work-hardens faster than steel, chrome-cobalt wires are supplied with various degrees of temper. The softest of these wires has a working range similar to that of wrought gold; the hardest temper, without heat treatment, has a range similar to 18/8 stainless steel. Heat treatment of the hardest chrome-cobalt alloys produces wire which is too brittle for most uses.

Prior to heat treatment chrome-cobalt alloy provides a very ductile wire which is easy to manipulate. After forming the archwire, heat treatment at $900°$ F. for a period of ten minutes produces a very resilient structure. Oven heat treatments are preferred since electrical heat treatment produces uneven heating with variable results. If annealing accidently occurs, heat treating the wire will not restore its maximum properties.

### HEAT TREATMENT OF GOLD WIRE

A fundamental understanding of the mechanics involved in the heat treating of gold alloys is imperative when one considers that one wire will soften due to the same heat treatment that causes another to harden. The changes that are produced in the strength and duc-

tility of a wrought gold alloy by heat treatment are due to the alterations in the gold-copper compound present in the alloy. All gold alloys are not subject to change through heat treatment. Those alloys which do not contain copper are changed to only a slight degree by this procedure. Copper improves the strength, hardness, and elasticity of the gold, while reducing its ductility. Copper also reduces the resistance to corrosion since it is easily attacked by sulphides which are present to varying degrees in different mouths. The strengthening effects of copper may be enhanced or retarded by the addition of other elements to the alloy such as platinum or palladium.

In order to uniformly soften most wrought gold wire it is heated to 1300° F. for approximately 10 minutes and then quenched. Softening of the alloy is produced as the gold-copper compound enters into solid solution at approximately 1300° F. When the wire is immediately quenched after reaching this temperature, the dissolved gold-copper compound is retained in supersaturated solution because of the rapid cooling. When all of the hardening elements are completely dissolved in each other in solid solution, the space lattice is free to move on the slip planes without interference. Because of this the wire is very soft and ductile and may be easily manipulated. This softened wire, if left standing at room temperature for several days, will become much harder. This phenomenon is known as "age-hardening" or "precipitation-hardening". The hardening effect may be accomplished in a shorter period of time by exposing the wire to a hardening heat treatment. If after quenching from 1300° F. the wire is reheated to approximately 840° F. and allowed to cool slowly from this temperature, the gold-copper compound tends to come out of solution. This

causes the formation of segregations of molecules which produce a locking effect on the space lattice and improve the resistance to slip. This dispersion of the segregation of molecules within the grains is usually too small to be seen with the optical microscope. The space lattice itself is also distorted to some degree, thus decreasing the number of planes on which slip can occur. In this way the material becomes stronger and more resilient. The American Dental Association Specification No. 7 for wrought gold alloys describes the hardening procedure as being accomplished by placing the wire in an oven at 840° F. for two minutes and then cooling to 480° F. over a 30 minute period after which the alloy is quenched in water. This procedure allows the proper amount of the gold-copper compound to come out of solution thereby producing the best strength while retaining the necessary ductility.

By not using heat treatment procedures the orthodontist is not obtaining the maximum properties from his alloys. Through heat treatment the strength of many alloys may be increased up to 80 percent over their strength in the soft condition. However, the quick method of air cooling results in only about one-quarter of the improvement which can be obtained by slower oven cooling. Since various compounds are formed at different temperatures, each wire will respond best to a certain heat treatment procedure for that particular wire. No one heat treatment will produce optimal results for all wires. Therefore, it is best for the orthodontist to follow the manufacturers' recommendations for the alloys used.

Besides precipitation hardening, there are two other ways by which the strength of wrought gold wire may be increased. One of these methods is cold-working. Practically all alloys

harden as their grain structure becomes broken up and the space lattice is distorted during cold-working. After the lattice has been permanently deformed to any degree, it develops increased resistance to further slip. This may be due to residual strain in the lattice which remains after permanent deformation has occurred or to fracturing of particles into the slip planes which then act as keys. This phenomenon can be demonstrated by bending and straightening a wire until it breaks. This type of hardening is easily relieved by heating the wires above a minimum recrystallization temperature. Recrystallization will take place and allow the atoms to return to a normal position in the space lattice. This process of cold-working followed by stress-relieving or annealing produces a more homogenous solution with refined microstructure. Some manufacturers offer wrought gold wires with a high degree of strain in the wire resulting from the last drawing or rolling operation. They may advertise these wires as having greater spring properties. However, these properties disappear upon exposure to the temperatures encountered in soldering. Most of the gold suppliers offer these wires in a softened condition. Thus it is well for the orthodontist to know fully the physical properties of the alloys as given by the manufacturers.

The third method of altering the strength of wrought gold wire is by varying the chemical composition. If metals are alloyed, the atoms of one metal will enter the lattice by replacing atoms of the other. This introduction of foreign atoms will cause distortion of the lattice, again making slip more difficult by producing a keying action. The greater the difference in atomic radius between the metals, the greater is the deformation of the lattice and the resultant hardness. Two elements

which are commonly added to the gold-copper alloy are platinum and palladium. Both raise the melting point, improve corrosion resistance, and increase hardness and strength during heat treatment. Binary alloys themselves are not satisfactory since they exhibit severe grain growth on heating and have poor ductility in the hardened state. The addition of rhodium, iridium, or cobalt reduces the rate of grain growth on heating. After age-hardening these complex gold alloys, values for tensile strength and hardness are produced which are very high for nonferrous metals.

## SOLDERING GOLD ALLOY

The drawing process which takes place during the fabrication of wrought gold wire changes the cast structure to a condensed fiber-like structure which gives the wire its strength, resiliency, and ductility. It is important that this fibrous wrought structure be maintained. Grain growth occurs in wrought gold alloys when the temperature of the metal is raised above the recrystallization point. It is accelerated as the temperature approaches the melting range of the metal. This may be seen in Figures 10 and 11, which show the amount of grain growth which occurs at various temperatures above the recrystallization point in a wrought gold wire. In Figure 11-above the fibrous structure has been almost completely replaced by large grains with a resultant loss in ductility. Figure 11-below shows the fused metal which is extremely brittle. The fusion temperature of this alloy was 1900° F. At this temperature the structure of the wire is changed back to that of the cast ingot from which the wire was made. The final grain size will be a factor of the relative degree of elevation of these temperatures, the lapsed period of time of temperature elevation, and the
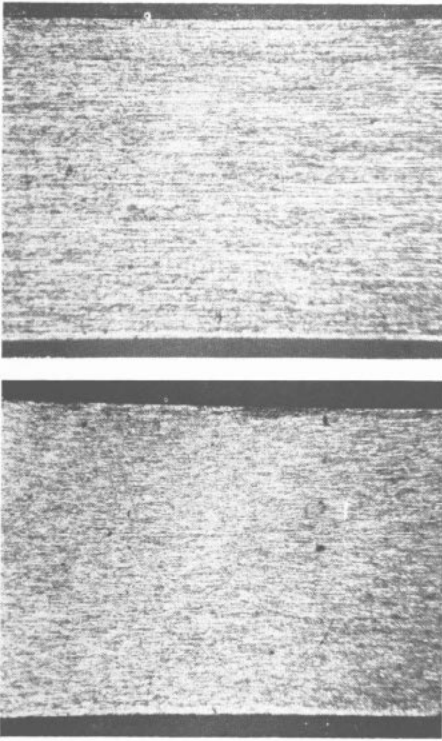
Fig. 10 Above, proper fibrous structure seen in a wrought gold alloy wire. X 200

Below, Structure of the same wire seen above after heating at 1450° F. for five minutes. X 200
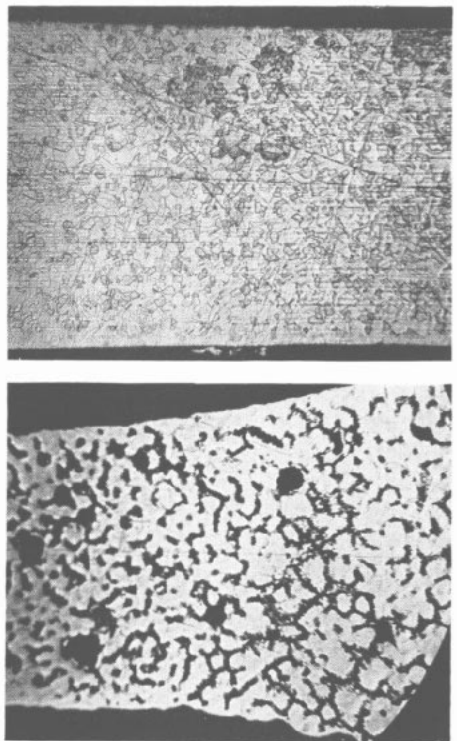
Fig. 11 Above, Structure of the same wire seen in Fig. 10, above, after heating at 1750° F. for five minutes. Note the large grains which have almost completely replaced the fibrous structure. X 200

Below, structure of the same wire seen in Fig. 10, above, after heating at 1950° F. for five minutes. The wire has fused, its structure changing back to that of the cast ingot from which it was drawn. X 200

amount of cold-working the alloy has undergone. One of the most frequent causes of the loss of the wrought structure is the heating of the wire during the soldering operation. The coarse grain structure which usually develops near the solder joint has less strength and is more brittle than the wrought structure. Since the greatest amount of stress is concentrated at the solder joint, it is here that breakage usually occurs. Therefore, the solder which is selected should have a melting range the upper limit of which is 150-200° F. below the lower limit of the melting range of the alloy to be soldered. This insures against heating the wire near its melting range. A gold alloy which is held for a period of time at a temperature 100-200° F. below its melting point will recrystallize and even undergo grain growth. If the metal has been cold-worked, it will undergo recrystallization at a lower temperature than one with less distorted grain structure.

The higher the fineness of a solder, the higher are its melting range and corrosion resistance. As a solder approaches less than 450 fine in quality,
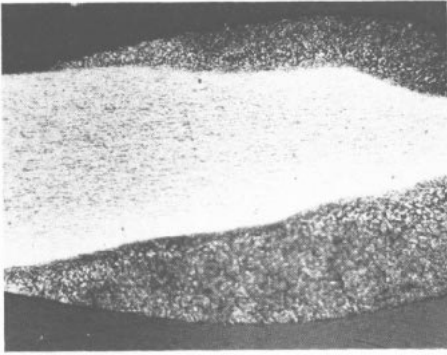
Fig. 12 Solder penetration into wrought gold wire. Heat was applied to the end of the wire at the right side of the photomicrograph resulting in a greater amount of diffusion at this end. X 200

its resistance to corrosion becomes low. For this reason appliances joined with very low fusing solders become unfit to remain continuously in the mouth. The final structure of the union which results after soldering and its response to heat treatment will be more like that of the wrought wire if a solder of high fineness is chosen. Platinum and palladium raise the fusion temperature of wrought gold alloys making possible the use of higher karat solders with relative safety. However, the strength of gold alloy solders increases as the fineness or gold content decreases. Therefore, solders with a gold content greater than 650 fine should not be used where considerable stresses will be involved.

Gold solders are alloys of gold, silver, copper, zinc, and tin with additional elements to improve resistance to oxidation. The high silver content solders spread freely with a minimum of diffusion into the wire itself. This diffusion of the solder into the wrought alloy takes place at temperatures which are suitable for soldering yet do not reduce the physical properties of the alloys. Microscopic examination of solder joints shows dispersion of solder

into the wrought alloy of varying degrees depending on the temperature reached, the length of time of the soldering operation, and the fusion temperature of the wrought wire. Figure 12 shows solder penetration into a wrought gold wire. The heat was applied to the end of the wire at the right side of the photomicrograph. The higher temperatures which developed at this end of the wire caused a higher degree of interalloying to take place. Wires with a low fusion temperature have an increased tendency to become penetrated by the solder. Figure 13 shows a severely overheated solder union between a gold alloy finger spring and a wrought gold archwire both of which had low fusion temperatures of approximately 1500° F. Obviously, a union such as this will be of no clinical use. A strong solder union can be obtained with only a small degree of diffusion between the solder and the parent alloy. This is demonstrated by the fact that failure of a gold-to-gold soldered bond usually occurs adjacent to the bond because of structural failure of the wire; the soldered union itself does not break apart. A properly soldered union between precious metals
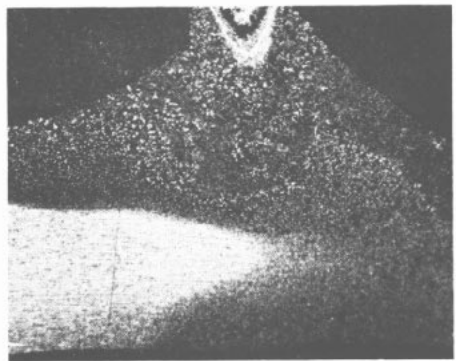


Fig. 13 A severely overheated solder union between a wrought gold finger spring and a gold archwire. A solder union such as this is of no clinical use. X 200
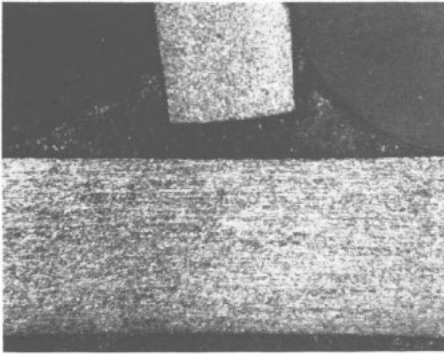
Fig. 14 A properly soldered union between two wrought gold wires. The proper amount of solder diffusion has taken place and yet the fibrous structure of both wires remains unchanged. X 200

is shown in Figure 14. The proper amount of solder diffusion has taken place and yet the fibrous structure of both wires remains unchanged. Increased diffusion is undesirable since it results in the formation of a new alloy which has a cast structure. This cast structure has reduced strength and is very brittle. In order that alloying can take place to any degree, the metal surface must be free of any oxide film when the solder is molten. To prevent this oxide from forming, a reducing flux is used and the soldering itself should be carried out in the reducing zone of the flame. This operation should be carried out as quickly as possible. Heat treatment temperatures of 800-900° F., for the purpose of strengthening an archwire, will not disturb properly soldered unions; it will actually make them stronger.

## DISCUSSION

Reputable manufacturers supply the physical properties of their materials along with information regarding heat treatment which are specific for their alloys. Unless advertised differently, the manufacturers generally market orthodontic wires in a heat-treated condition so as to offer the best combination of strength, resiliency, and ductility. For the effective clinical use and control of orthodontic appliances it is essential to have an understanding of the character and degree of the effects which are produced in the structural material of the appliance due to applied forces and the ability of the material to withstand these forces. Unfortunately, in his training, the orthodontist usually pursues very little study of the laws governing the mechanics of forces or the effects produced by the forces on materials. This leads to frequent abuse of the materials which reflects itself in a lowered degree of treatment efficiency. Interest on the part of orthodontists in structural matters connected with their appliances would result in substantial savings in time and materials and increased service to the public.

## PREPARATION OF SPECIMENS

The metal specimens are imbedded in acrylic cylinders and cured under pressure to prevent porosity which would interfere with polishing. Rough polishing is accomplished by drawing the specimen across emery paper on a flat surface rotating the specimen at right angles between each grade of paper from no. 1 through no. 0000. Fine polishing is accomplished by using, in order, a water suspension of alundum powder on a revolving wheel, a water suspension of alumina, and finally rouge on a chamois wheel, using very light pressure.

Polishing causes the surface layer of metal to flow slightly. This produces a thin film of amorphous metal which hides the true grain structure. Etching reagents are used which dissolve this layer and then attack the alloy at a differential rate. The material at the grain boundaries is attacked more rapidly and, as a result, these boundaries show up dark in the photo-

micrographs. This differential rate of attack delineates changes in crystal orientation and concentration of alloying elements. The etching reagent used for stainless steel is cupric sulfate; that used for gold specimens is equal parts of ten percent solutions of potassium cyanide and ammonium persulfate. After etching, the specimen is rinsed in ethyl alcohol and is then ready for viewing under the microscope.

In order to obtain electron photomicrographs a replica technique is used. A one percent solution of formvar in chloroform is a material which will reproduce faithfully the surface features of the metal.[9] This dilute solution of plastic in a volatile solvent is placed on the etched metal surface. Upon evaporation of the solvent there remains a film of plastic which is then backed with a thin ten percent solution of celloidin. This combination of formvar and celloidin produces a replica film of high contrast which is easily removed from the metal surface. This replica is then mounted on a copper grid and carbonized in order to stabilize it in the electron beam. This is accomplished by placing the replica in a vacuum chamber. A current is then passed through two pointed carbon rods which are held in contact inside the chamber. This results in carbon atoms evaporating from the rods and recondensing on the surface of the replica. It is then shadowed in a high vacuum with chromium at an angle of 45 degrees. This produces a considerably increased contrast of surface elevations and depressions. It is then ready for examination in the electron microscope. After the electron beam passes through the replica it is magnified to produce

an image on a fluorescent screen. The contrast which is seen in the image is the result of differences in scattering power as the electrons pass through the thick and thin parts of the replica, or the parts which have different atomic composition.

A fairly new technique has been developed which allows direct examination of solid surfaces by means of scattered or reflected electrons.[10] Although it has many limitations, this method will undoubtedly have important uses in metallurgy.

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