The Low Temperature Heat-treatment of Stainless Steel for Orthodontics

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At the Charles H. Tweed Foundation for Orthodontic Research in 1949, Dr. Emery Fraser introduced a low-temperature heat-treatment for increasing the effectiveness of stainless steel appliances in orthodontics. Some controversy about the worth of such a heat-treatment suggested this study of the mechanical behavior of stainless steel wire before and after various heat-treatments.

There is already a large amount of information available from earlier studies (1-7) of the effect of heat-treatment on the mechanical properties of cold-worked stainless steel. The significance of the present work, however, derives from the use of severely cold-worked orthodontic wire, which has received only limited attention, and a typical archwire construction as experimental materials.

In addition, the results of this study do provide important information for evaluating the worth of the low-temperature heat-treatment suggested for orthodontic appliances.

A considerable amount of previous work and some of the present work concerns the behavior of test specimens deformed in simple tension. Therefore, a brief review of the method of testing and the meaning of the terms, stress, strain, elastic modulus, elastic strength, tensile strength, etc., will probably be helpful in discussion of the effects of heat-treatment.

For this purpose, consider a square metal bar, one inch on a side, tightly gripped at one end and suspended so that it hangs vertically downward with a weight of 1000 pounds attached to the lower free end. The cross-section of the bar is one square inch, while the weight or force is 1000 pounds. Therefore, the intensity of this force, called the stress, is 1000 pounds per square inch. If the force is doubled, the stress increases to 2000 pounds per square inch. Now if the force of 1000 pounds is attached to a bar of only one-half the previous cross-section, the stress is likewise increased twofold. Thus the stress is equal to the force divided by the area of the cross-section over which the force acts.

If the bar is steel, a stress of 1000 psi (pounds per square inch) results in an extension of only about 0.0004 inches for every 12-inch length of the bar. When the force causing this stress is removed, the bar quickly contracts to its initial length. The deformation is recoverable and is described as elastic. It is the same kind of deformation observed when a rubber band is stretched and then released.* As the stress in the steel bar is increased, the extension of the bar increases proportionally. If the stress is doubled, the extension increases to 0.0008 inches for every 12-inch length. This response of extension to stress is a fundamental characteristic of elastic deformation.

The extension of the tensile bar is

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* One important and obvious difference between steel and rubber is the amount of elastic deformation possible in the two materials. Under the same conditions, the extension of steel will be only about 1/100,000 that of rubber.

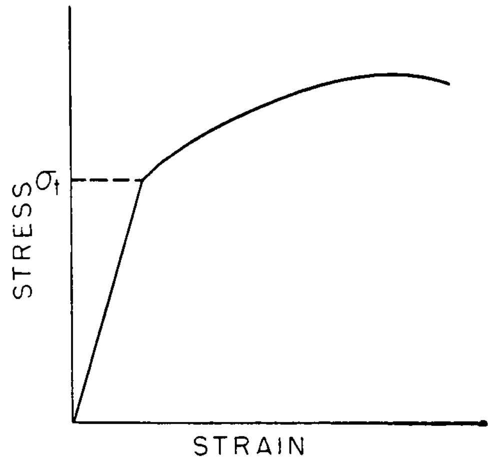

Fig. 1—A schematic tensile stress-strain curve.

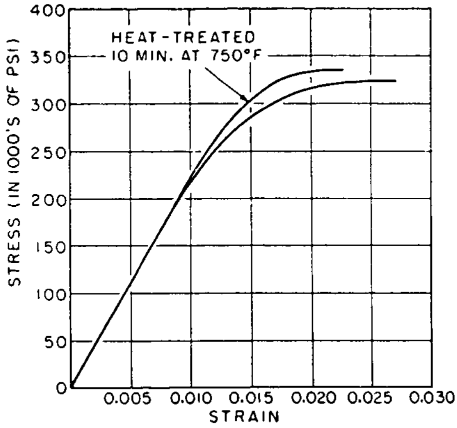

Fig. 2—Tensile stress-strain curves for 0.020 round wire in the as-received condition (lower curve) and after heat-treatment for 10 minutes at 750° F (upper curve).

described in terms of "every 12-inch length". Extension must be described in this way because the total extension of the bar can be doubled by merely doubling the length, even though the stress is not changed. A bar exactly 12-inches long stretches 0.0004 inches when the stress is 1000 psi, and a 24-inch bar lengthens by 0.0008 inches under the same stress. It makes little difference whether the extension resulting from a stress of 1000 psi is expressed as "0.0004 inches for every 12-inch length" or 0.000033 inches per inch of length, although the latter expression is usually preferred. The extension per unit of length is known as strain.

The elastic behavior of a metal bar stressed in tension is easily pictured with a graph such as that shown in figure 1. The straight line in this graph describes the relationship between elastic stresses and strains. If the stress does not exceed the value (or sigma-sub-t), the deformation is elastic and completely recoverable when the force responsible for the stress is removed. The stiffness of the metal is measured by the slope of this line. For example, the slope for a stainless steel bar is nearly twice as steep as the slope for a bar of a common gold-alloy. Therefore, stainless steel is nearly twice as stiff as the gold-alloy. The slope of this line is called the modulus of elasticity.

When the stress is raised to a level higher than (or sigma-sub-t), the strain is no longer even approximately proportional to the stress. This is apparent from the curved line drawn in fig. 1. If the force responsible for the stress is now completely removed, the bar will not contract to its original length. It will have acquired a permanent "set", which means that it has deformed plastically. For a particular material, the stress cannot be increased beyond a definite maximum value at which the bar undergoes very localized plastic deformation and finally breaks. This maximum stress is known as the tensile strength. The total strain in the bar when it breaks, multiplied by 100, is a measure of the ductility of the material and is referred to as the percent elongation.

The stress-strain curve of figure 1 is, of course, schematic. There is no difficulty in defining elastic strength in this case. It is equal to the stress, however, the transition from elastic to plastic deformation in most engineering metals is much less distinct than it is in figure 1 and so the expression "elastic strength" sometimes requires more precise definition.[9] But precise definitions may be avoided if elastic strength is now considered, in a liberal sense, as the initial resistance to plastic deformation, instead of a well-defined stress at which plastic deformation begins.

To illustrate the behavior of an engineering metal, tensile stress-strain curves for 0.020 inch diameter stainless steel wire are presented in figure 2. The lower curve was obtained from wire in the condition in which it was received; the upper curve after annealing this wire for ten minutes at 750° F. Details of the procedure for constructing these curves are discussed later in the paper. It is apparent that heat-treatment has extended somewhat the straight line portion of the stress-strain curve. This is the most important feature of these data and means that an appreciable increase in elastic strength has resulted from the heat-treatment. The significance of this increase will be emphasized again at another place in the paper.

PREVIOUS WORK

Because of its constitution, stainless steel can be strengthened only by plastic deformation or "cold-working". A very high tensile strength may be obtained in this way but the elastic strength after such working is frequently low and unsatisfactory for many applications. This condition has prompted several careful studies (1-4) of means for improving the elastic strength of cold-worked stainless steel, and proper heat-treatment is now considered the most effective was to accomplish this improvement.

Heat-treatments varying from 30 minutes at 950° F to 100 hours at 400° F have been recommended. The low-temperature, short-time heat treatments have been advocated to avoid the discoloration caused by annealing at the higher temperatures and to eliminate any chance of impairing the corrosion resistance. Discoloration is often not easily avoided when the temperature is in the upper part of the recommended range, but test results have been reported[6] which show that short-time, high temperature' heat-treatments should not be expected to alter the corrosion resistance.

In addition to the increase in elastic strength, other effects reported to result from heat-treatment are:

1. an increase in the modulus of elasticity which is reported most often as 2 to 5 percent, but in one case[6] as 15 percent,
2. an increase of several percent in the tensile strength after cold-working an amount approaching that performed on orthodontic wire,
3. A slight increase in the percent elongation after moderate cold-working but a decrease following more severe cold-working.
4. an improvement in the resistance to fatigue, or failure under alternating stresses,[2]
5. a slight increase in toughness.[2]

EXPERIMENTAL WORK

The changes in mechanical properties resulting from heat-treatment are most conveniently studied by conducting simple tension tests on 0.020 inch round wire and 0.021 x 0.025 inch rectangular wire. A straight length of wire is, of course, not exactly equivalent to an orthodontic appliance. Therefore to meet any such objection to tension testing, and to provide more direct measurements of the effect of heat-treatment, experiments were also performed with rectangular wire in which closing loops were formed.

Wire for the tension tests was obtained from several sources. Specimens with a 5-inch test length were annealed at 500° F, 750° F, and 820 ° F for different times from 3 to 120 minutes. Five specimens were tested for nearly

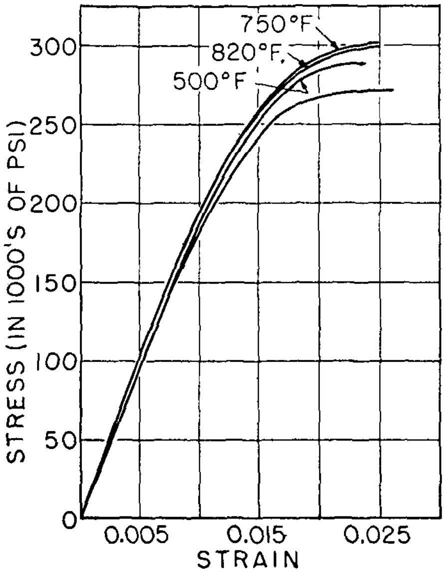

Fig. 3—Tensile stress-strain curves for 0.021 x 0.025 rectangular wire in the as-received condition (lowest, unlabelled curve) and after heat-treatment of 20 minutes at 500° F, and 10 minutes at 750° and 820° F.

all combinations of time and temperature. In general, it was found that 20 minutes at 500° F and 10 minutes at 750° F and 820° F were adequate for reproducible test results and that longer times at these temperatures did not cause additional changes of any consequence. However, any conclusions about the proper time-temperature combination must be only tentative since the work was concerned primarily with the effect of the heat-treatment and only secondarily with the optimum heat-treating conditions.

The tension tests were carried out with a machine that provided a graphical record of the applied force and the extension of the specimen. This information is readily converted into stress and strain.

Figure 2 contains typical tensile stress-strain curves for as-received and heat-treated round wire and illustrates the most important effect of heat-treatment, namely the marked increase in elastic strength. The influence of the heat-treating temperature is apparent from the stress-strain curves of figure 3 for rectangular wire in the as-received condition and after heat-treatment at 500° F, 750° F and 820° F. The increase in elastic strength is more pronounced after heat-treatment at the higher temperatures. In figure 3, the position of the 820° F curve slightly below the 750° F curve seems hardly significant. Subject to the accuracy of the testing, it was difficult in the many tests carried out to observe any consistent difference between the results of annealing at these temperatures.

The presentation of more tensile data would add little to the argument of the paper since figures 2 and 3 adequately describe the results of these studies.

The next experiments were concerned with the effect of heat-treatment on the force-deflection characteristics of closing loops. The closing loop was chosen as a typical archwire construction, and, at the same time, was a convenient test specimen. Two kinds of loops were formed from 0.021 x 0.025 rectangular wire. In one, type A, the legs were brought into contact, while in the other, type B, the legs were separated by about 1/64 of an inch. Complete dimensions and the final shape of the loops before testing are shown in sketches, drawn approximately to scale and included in figures 4 and 5.

Type A loop was supported by the upper hook and weights were attached to the lower. The heavy arrows represent the force-applied to the loop in this way. Two references marks, a distance L-o apart, were scratched on each loop and their location is shown in the sketches. L-o on all loops was about ⅛ of an inch and was accurately determined with a measuring microscope before the test. In testing, the

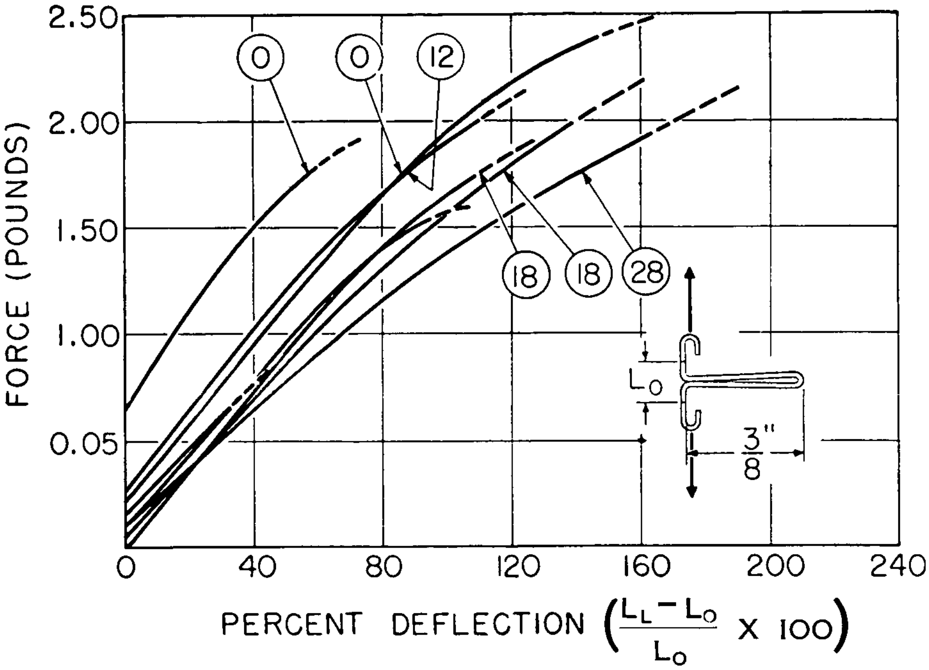

Fig. 4—The force-deflection characteristics of typical non-heat treated closing loops.

weight on the lower hook was increased by small amounts, and after every addition, the distance, L-l, between the two reference marks, was measured with the microscope. In this way, between 15 and 20 observations were made in most tests. The difference between L-l and L-o divided by L-o, and multiplied by 100, is described as the "percent deflection" and is used as a measure of the opening of the loop caused by the applied force.

Force-deflection curves for eight of the A loops tested without heat-treatment are presented in figure 4. The loops broke through the bend either as the last increment of weight was added or immediately after. It was impossible therefore to observe the force and deflection at fracture. The curves are extended with dashed lines to indicate this condition. The encircled numbers for the different curves represent the percent deflection which remains in the loops after the force has been increased to 1.76 pounds and then removed.

All of the A loops were formed by an orthodontist with conventional instruments and were made as nearly alike as possible. Despite careful preparation, however, figure 4 reveals a fairly wide variation in the force-deflection characteristics of the individual loops. The reason for this is the variable amount of cold-working that can be introduced into the bend when pinching it with pliers to bring the legs of a loop into contact. The cold-working may be just sufficient to close the loop, but it could easily be greater than the necessary amount, although the finished loop would appear the same in both cases. Loops of this type were not tested after heat-treatment because of the possibility that their non-uniform behavior might tend to obscure the effects of the heat-treatment. This does not mean, however, that heat-treatment will be any less significant

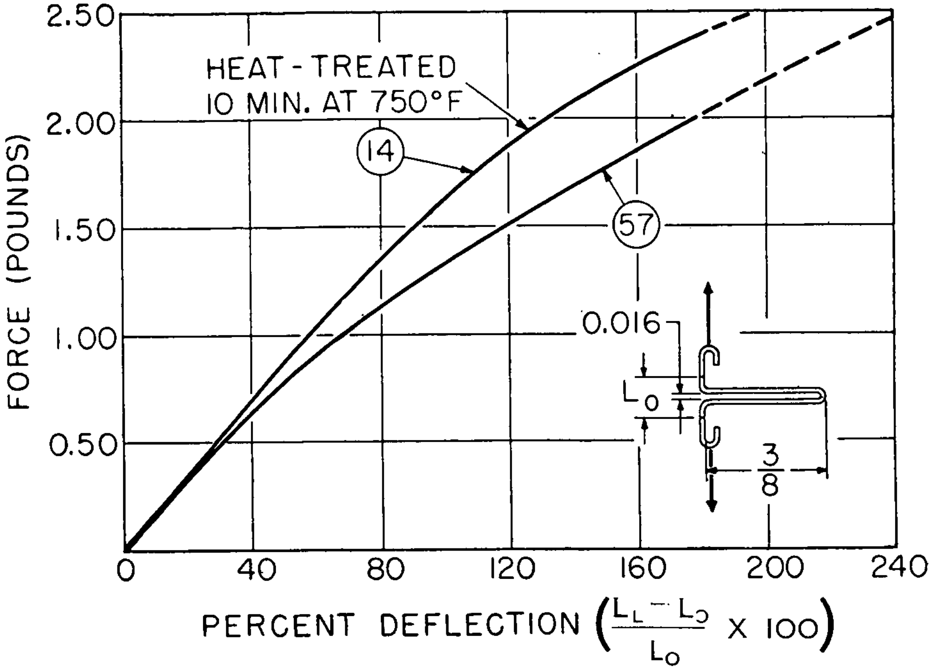

Fig. 5—Averaged force-deflection characteristics of closing loops with separated legs after forming (lower curve) and after a heat-treatment of 10 minutes at 750° F.

for such loops. But it would be difficult to compare loops before and after heat-treatment if the characteristics of all were not approximately the same before. Although these observations do not pertain directly to the subject of heat-treatment, they seemed interesting enough to warrant including them in the paper.

Because of these results, the type B loops with separated legs were prepared and tested both before and after a heat-treatment of 10 minutes at 750° F. The cold-working of the bend in this type of loop should be less variable since the legs are separated and this spacing is effectively a gauge which determines when the bending should be stopped. A loop with somewhat more reproducible properties can be expected, and it was found that the force-deflection characteristics of such loops were sufficiently alike that only averaged data could be used to prepare legible curves for figure 5. The curves for the loops before and after heat-treatment were drawn from the averaged results of four and five tests respectively. The encircled numbers and dashed lines extending the curves have the same meaning as before.

A pronounced increase in elastic strength is again observed to be the significant effect of heat-treatment. In general, for all values of the applied force, the heat-treated loops have been strengthened considerably. Notice that the deflection remaining after application and removal of the 1.76 pound force is reduced by a factor of about 4 in the heat-treated loops.

DISCUSSION

Both the present work and a large amount of previous work have established that heat-treatment does affect the mechanical properties of cold-worked stainless steel, and in particular causes a marked increase in elastic strength. There is very good reason to conclude that in orthodontics, as in other applications of stainless steel, it is the improved elastic strength that is most significant.

For example, it is more likely that in a working appliance, made elastically stronger by heat-treatment, all of the distortion will be elastic and recoverable, and the forces produced by the distortion will be the maximum possible. This is perhaps the most important benefit derived from heat-treatment and is illustrated by the curves of figure 5. These curves show that for any deflection greater than that at which the curves diverge, the heat-treated loop applies the larger force and contains much less, if any, permanent deflection after the force is removed.

Other changes in elastic modulus, tensile strength, etc., resulting from the heat-treatment of stainless steel appear to be of only secondary importance. This statement is made with some reservation however, for an increased elastic modulus could mean a stiffer and more powerful appliance and this may be of value to some in orthodontics. But limiting the significance of this possibility is the large amount of available data which shows that the elastic modulus is seldom increased by as much as 10 percent.

The improvement in the elastic strength of cold-worked stainless steel brought about by proper heat-treatment is neither new nor strange to the materials engineer. Actually the response of many cold-worked metals to a low-temperature heat-treatment is similar to that of stainless steel. [1 7 8] This general response results most often from the elimination of so-called residual stresses which remain "locked-up" within a metal even after the forces of cold-working are removed.

When a force is subsequently applied to a cold-worked metal, the actual stresses are the sum of the residual stresses and those produced by the force. Therefore very high stresses and plastic deformation may occur when only a small force is applied.

A bent loop provides an example of this possibility. The residual stresses are most likely to be tensile at the inside surface and compressive at the outside surface of the bend. As the loop is opened, the inside is subjected to additional tension and the outside to additional compression. As a result, the loop will acquire a permanent "set" under a smaller force than if the residual stresses were absent.

The need for removing residual stress is not limited to orthodontics. Many metal articles formed of cold-worked sheet, rod, wire, etc., and intended for applications which require a high elastic strength are frequently heat-treated. The heat-treatment is commonly described as a stress-relief anneal.

SUMMARY

It was the purpose of this work to obtain information for evaluating the worth of the low-temperature heat-treatment recently suggested for orthodontic appliances of stainless steel. The results may be summarized as follows:

1. Experiments with 0.020 round and 0.021 x 0.025 rectangular wire and a typical closing loop formed from rectangular wire show that heat-treatment does result in changes in mechanical behavior, and in particular causes a marked increase in elastic strength.
2. The increased elastic strength appears to be the most significant effect of heat-treatment, because an elastically stronger working appliance is more likely to return to its original shape, while applying maximum force, and not suffer any permanent set.
3. From a limited consideration of

heat-treating conditions, it was found that 20 minutes at 500° F and 10 minutes at 750° F and 820° F were adequate for reproducible results, and longer times at the various temperatures were unnecessary. The effect of heat-treatment at 750° F and 820° F was somewhat more pronounced than at 500° F, although little difference could be found in the results of heat-treatment at 750° F and 820° F.

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