Heat Treating

How annealing, stress relief and aging each affect the mechanical properties of spring materials

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In the metals industry, there are numerous steps from the raw material to a finished product. For our purposes here, the finished product is a spring (which, in turn, will be used as the raw product in producing someone else's finished product). Being involved in the supply of raw materials to the spring industry, I am frequently asked for assistance and recommendations for virtually all of the various mechanical and physical properties of the many different metals that are typically used to produce springs. The second most-asked question involves the heat treatment of the metal used to produce the spring.

In many cases, when the spring producer is working from either a print or customer specification, the heat treatment may be specified on these documents or other referenced specifications; however, this is not always the case. Many times, the final heat treatments, if any, are left to the spring producer who must then decide what is required to meet the customer's expectations. This is when a better understanding of what the term "heat treatment" actually means can help simplify one's efforts.

The intent of this paper is to briefly explore what happens to the mechanical properties of the metals used to produce springs when specific heat treatments are used. No attempt is made to go into a rigorous metallurgical explanation of what happens to the metal; such explanations would be of little interest or value to most people. Rather, a variety of charts and graphs shows what has happened to the mechanical properties of the metal when an appropriate heat treatment has been used. In addition, the data presented here covers only a very minute portion of that available for each of the various materials.

Definitions

The term "heat treatment" is, in and of itself, only a very generic term. It covers all specific methods similar to the way a tent or tarpaulin covers a crowd of distinctly different people during a rainstorm. We will concentrate only on those forms of heat treatment that are most commonly used in the spring industry: annealing, stress relieving and aging. There are many other terms that fit under the heat-treatment umbrella, but these three are the most commonly encountered. Even within these three, one can find further sub-classifications, but exploring them in this article would only add confusion.

By way of introduction, the following definitions may be applied (all definitions are taken from the ASM Materials Engineering Dictionary):

Heat Treatment: Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.(1)

Annealing (metals): A generic term denoting a treatment consisting of heating to and holding at a suitable temperature, followed by cooling at a suitable rate, used primarily to soften metallic materials, but also to simultaneously produce desired changes in other properties or in microstructure. (2)

Stress Relieving: Heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses. (3)

Aging (heat treatment): A change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or a heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and nonferrous alloys) or after a cold-working operation (strain aging). The change in properties is often, but not always, due to a phase change (precipitation), but never involves a change in chemical composition of the metal or alloy. (4)

To simplify explanations, I group aging and precipitation hardening into a single category. Most typically, these two terms are used interchangeably; however, similar to heat treatment, aging is again an all-encompassing term.

I will cover each of these heat treatments in the order presented above. Each treatment is usually used independently on the finished product. However, as in all of life, there are exceptions to this statement, but not to be pursued today. In presenting the data, I have tried to take examples of typical materials that the springmaker may use on a regular basis; that is, some of the more common materials.

The following facts should be stated regarding the information that is presented:

- Every data point represents an average of three to five individual tests on material in the same condition. Statistical information for data spread is not included for brevity, but the spread is rarely broad.
- All data presented is "real-world," taken from actual materials produced for sale. The exception is the data presented for annealing. This information was generated to support the development of processing practices.
- Where "trend lines" are presented, these lines have been calculated using third-order polynomials. Other methods may be appropriate, but I have found this method to be the best for my purposes.
- All tensile data was obtained using an Instron model 4204 tensile tester. Testing methods were based upon ASTM A370 and E8. Although immaterial, the gage length used for all samples was two inches. (The gage length affects only any reported elongation values, and none are presented in this paper.) Testing was performed using strain-rate control. Crosshead separation should produce virtually identical conclusions. The measurement technique employed for material certification is usually based upon the requirements of the end user.

Annealing

As defined above, the heat-treatment process of annealing is typically used to soften a metal so that subsequent operations may take place. As a metals producer, the annealing operation is very important, as we usually go through a series of cold-working and annealing cycles so that we can provide customers with a product that has the desired mechanical property characteristics. For spring wire, the final product is usually in the highly cold-worked state commonly known as the "spring-tempered" condition, although material in the annealed condition is not uncommon. Strip product is quite often sold in the annealed condition and subsequently aged to increase the strength; however, cold-worked strip is also prevalent.

A springmaker may anneal the metal (or purchase it already annealed) so that it can be worked more easily due to the relatively low tensile strength of the material. The material may be processed in the cold-worked condition and then annealed as part of the overall heat-treating process, as is required by some of the AMS and ASTM specifications. With some exceptions, annealed material that is subsequently aged does not attain the higher tensile properties possible with material that has been cold worked and then aged.

Regardless of the reason employed, the annealing process softens the metal by re-crystallization. In the simplest of terms, the material returns to a softened state that allows further cold working, if required. Some of the parameters that are important in annealing are: temperature, time and cooling method. Figure 1 and Table 1 show how some of these factors interact.

Figure 1 presents data that was obtained from 0.500" diameter X-750 that had been cold worked and required annealing to make the material soft so that additional cold working could be performed. The material had a grain structure that was elongated in the drawing direction and had a hardness of approximately 35 HRC. Since the grains were elongated, a grain size determination is not applicable. The annealing study was performed at a variety of temperatures with the annealing time held constant at 15 minutes (at temperature). The resulting Rockwell B and grain sizes are presented in the plotted data. Using this data, the choice of annealing temperature is made to yield the combination of properties required by the customer.

Table 1 presents data showing the effect other variables have upon the hardness of the annealed product. In this case, the material is 0.135" diameter Elgiloy that has been annealed at a constant temperature of 2100°F but with variable time at temperature and employing different cooling (quenching) methods.

Time (minutes)	Hardness - HB			ASTM Grain Size		
	W.Q.	A.C.	F.C.	W.Q.	A.C.	F.C.
1	95.1	92.9	90.4	7.5	7.0	6.0
5	90.5	88.5	87.7	5.5	6.0	4.5
30	87.7	84.6	89.1	4.5	4.5	3.5
60	89.1	84.3	86.6	4.0	3.5	3.0

W.Q. = Water Quench / A.C. = Air Cool / F.C. = Furnace Cool

Table 1. Study showing the effect of varying the annealing time and quenching method on the hardness and grain size of a 0.135" diameter Elgiloy wire.

Again, the metals producer will use such information to help establish processing practices to yield the material characteristics desired by the

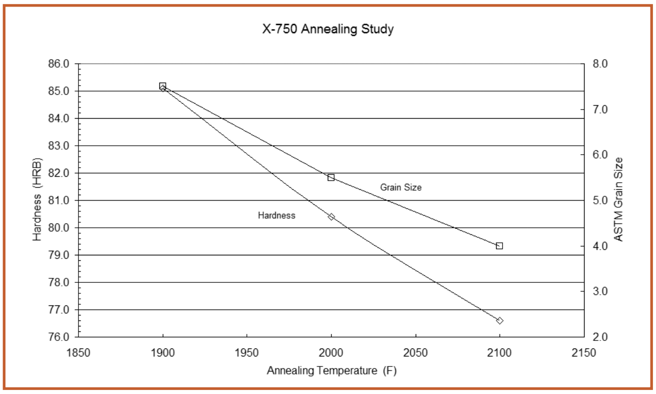

Figure 1: Annealing study on 0.500" X-750 wire, showing the effect of annealing temperature on Rockwell hardness and ASTM grain size.

customer. Such information can also be useful to the spring manufacturer in a situation where a material must be softened in order to perform subsequent forming work. In such cases, close work with the metals supplier is necessary so that a material is not rendered useless.

Stress Relieving

Stress relieving is one of the two most common heat treating operations that a spring manufacturer is likely to encounter. The other is the aging treatment, to be discussed later. Stress relieving does exactly as the name implies, it relieves the stresses that occur as a result of the spring forming operation. It also returns the material to the strength levels prior to the forming operation and can actually increase the strength to levels greater than originally supplied. Studies have shown that the interstitial elements pin the point and line defects in the atomic structure of the metal, resulting in an increase in the mechanical strength. As in the annealing heat treatment, there are variables that affect the final outcome – most typically, the temperature and time employed. These two parameters are the most potent in their effect on the final properties.

Figures 2 - 5 are plots of stress relieving studies for three of the most commonly used spring materials – hard-drawn MB, music wire and T-302 stainless steel. The type of data presented here for these materials is available for nearly all materials. If not, quick examination of the data presented here shows that, although slightly time consuming, the generation of such data is not an excessively complex undertaking.

Figures 2 and 3 are for 0.080" diameter hard-drawn MB carbon steel. In Figure 2 a trend line has been superimposed on the data. Such practice helps not only to smooth the data, but it also gives a very nice presentation of the data so that one can easily determine the point of optimum properties. A quick check of any of the spring manuals will show that the recommended stress relieving temperatures fall within those predicted by the data in Figure 2. In fact, this is exactly how the original recommendations for stress relieving were developed. Figure 3 takes the process one step further: the refinement of the time required to complete the process of stress relieving. In this case, the experiment used two defined temperatures (350°F and 450°F) but varied the time at these temperatures from two to 120 minutes. From Figure 3, one can easily determine that the bulk of the stress relieving had taken place when the part had been exposed at temperature for a minimum of 20 - 30 minutes.

Figure 4 is for 0.080" diameter music wire that has been stress relieved for one hour over a wide temperature range. The trend line clearly defines the optimum properties for this material. Performing tests with constant temperature while the time was varied yields the same conclusion as for Hard Drawn MB carbon steel: The bulk of the stress relieving had taken place by the time the material had been exposed at temperature for 30 minutes.

Figure 5, below, is for 0.076" diameter T-302 stainless steel, the third alloy that is very commonly used for spring applications. In this case, the time (10 min., 30 min. and 60 min.) data has been included on the temperature plot. This method is beneficial in that we can readily define the optimum temperature (for maximum properties). It also lets us see visually that, by the time the spring has been exposed at temperature for 30 minutes, the majority of the stress relieving has taken place. This method merely combines all of the data on one plot and allows more immediate visualization of what is occurring.

Aging

The definition of aging previously presented quite clearly states that this process results in a change in material properties but not chemical composition. This statement is true but applies only to the bulk chemical analysis of the material. In fact, what occurs is the precipitation of an additional phase (or phases) that do have different chemical compositions.

As I had stated, aging covers a multitude of processes – none of which I am going to go into in detail, as the truly important part of aging is that it typically increases the strength of the material. For many of the spring alloys, this occurs by a combination of both cold working and subsequent aging. The resulting material has very high tensile and yield strengths compared to the starting product.

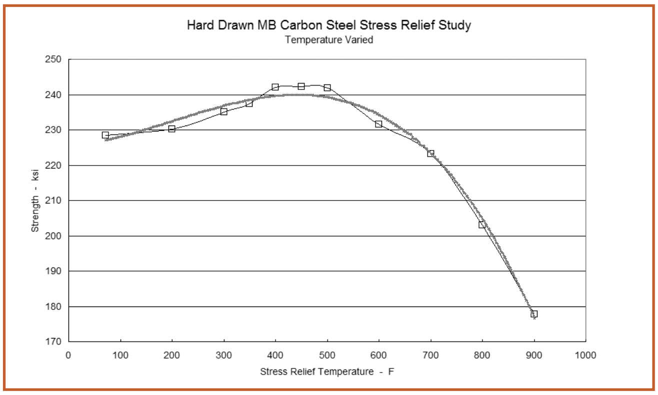

Figure 2: Stress relieving study of 0.080" hard-drawn MB carbon steel. Time at temperature was set at one hour while the temperature varied. A trend line is used to smooth data.

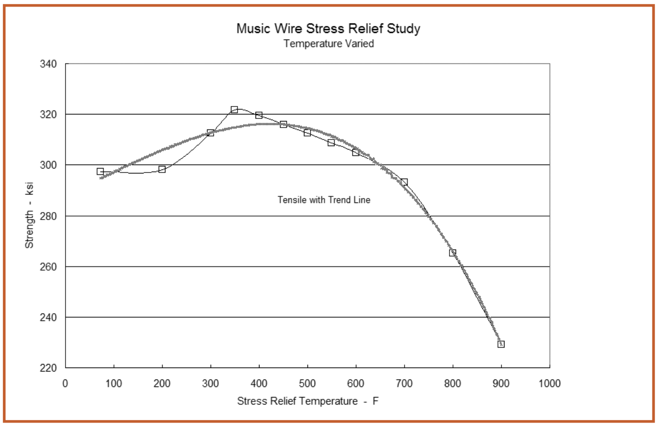

Figure 4: Stress relief study of 0.080" music wire. The time was fixed at one hour and the temperature varied.

(Again, remember that there are always exceptions to the rule.)

Figures 6 and 7 are presented for 0.078" 17-7PH and 0.057" A-286, respectively. Figure 6, left, is the superposition of the aging time onto the aging temperature plot, similar to that shown for the T-302 stainless. In the case of 17-7PH in Condition C, all governing specifications require that the material be aged at 900°F for one hour. I have included this plot of a time-temperature study to show exactly how this particular set of parameters was established. Examination of the data clearly shows that one hour at 900°F provides the optimum tensile strength for this material. Once exceeded, the properties begin to decrease; in fact, they do so quite rapidly.

Figure 7 presents data for 0.057" diameter A-286 in the same manner as Figure 6 does for 17-7PH. Many times, A-286 is used in the annealed or slightly cold-worked condition. In this case, the A-286 has been cold worked to a somewhat moderate spring temper condition and then aged.

Unlike 17-7, there is no specification that defines what the spring temper condition is for A-286. (This may be arguable, as there are some AMS specifications that clearly dictate how the material is to be processed; however, these specifications are not typically employed in the normal course of spring manufacturing.) This condition is either loosely defined by the material supplier or by customer specification. This plot is somewhat of a compendium of what I have experienced over the years as to how many people age spring tempered A-286. The typical temperature range is 1100°F to approximately 1250°F for time ranging from 60 minutes to 960 minutes (16 hours). In this study, both temperature and time have been expanded to provide a more complete picture of the aging process.

Concluding Remarks

The information presented in this article is by no means exhaustive. Each set of data is relatively well represented statistically by virtue of the number of repetitive tests that were performed. However, to have a far better picture of what really occurs, such data should be generated using multiple heats over a period of time. Such techniques are how specification requirements come into existence in the first place.

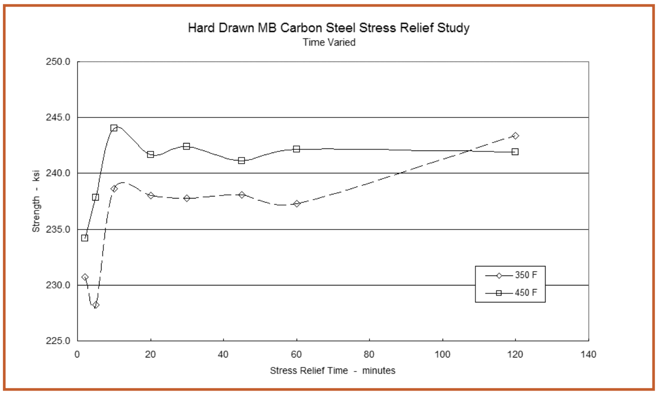

Figure 3: Stress relief study of 0.080" carbon steel wire where the temperature was held constant and the time varied from two to 120 minutes.

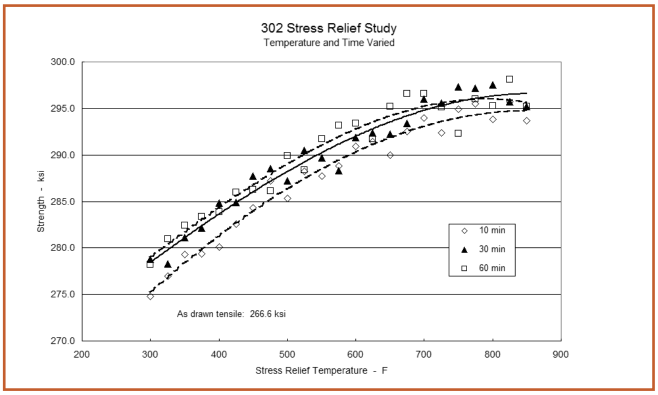

Figure 5: Stress relief study of 0.076" diameter T-302 stainless steel. Both temperature and time varied. Trend lines are used to smooth data.

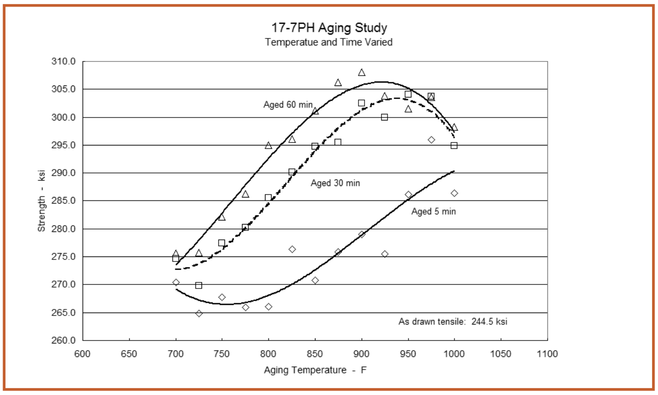

Figure 6: Aging study of 0.078" 17-7PH in Condition C. Various aging times are superimposed upon the temperature curves to show optimum property development. Trend lines are used to smooth data.

To some, this information may seem to be somewhat academic, as there are already "standards" and "rules" governing many of the materials presented. Although this is true, the number of inquiries that I receive every month belies the fact that this information is readily available or even fully understood.

I have attempted to pique people's curiosities as to where this information comes from, how it is generated and how it can be used. If one were to take this a step further, the question that could (and should) be asked is, "How does this truly affect the performance of the springs that I produce?"

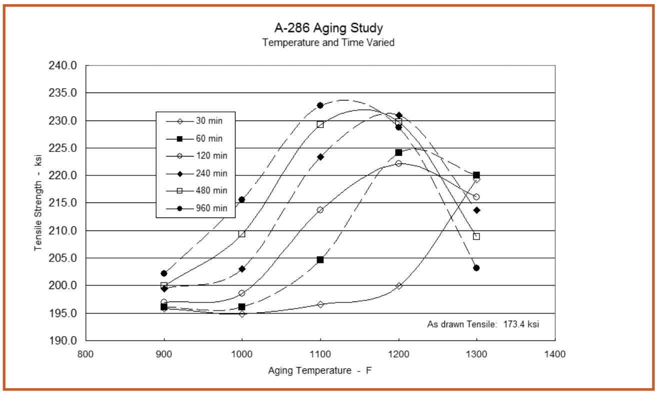

Figure 7: Aging study of 0.057" A-286. Time and temperature were varied to show development of optimum properties for a variety of aging parameters.

Acknowledgements

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References

1. ASM Materials Engineering Dictionary, Edited by J.R. Davis & Associates, ASM International, 1992, p. 202.
2 Ibidem, p. 19.
3 Ibidem, p. 455.
4 Ibidem, p. 10.

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Following graduate school, he spent four years as a materials scientist for the Materials Laboratory in the United States Air Force at Wright Patterson Air Force Base. He then joined National-Standard Co., where he worked as the manager of new product development for 20 years. In 1998, he joined Elgiloy Specialty Metals in Elgin, IL, where he is general manager of wire.

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