Technically Speaking

with Luke Zubek

A Technical Review of Precipitation Hardening Stainless Steel Grades

The challenge with most engineering materials is finding something that is soft enough to be formed into a useful shape and then strong enough to be of practical use. This issue is reflected in the spring materials that are in use today. Steel wire or strip can be hardened primarily in two ways: cold working, or quenching and tempering. Stainless steels can also be hardened in a similar fashion, but an additional strengthening path exists called "age hardening" or "precipitation hardening."

Precipitation Hardening

In 1906, precipitation hardening of metals was accidentally discovered on the aluminum-copper alloy called "Duralumin" by the German metallurgist Alfred Wilm. It took about 15 years after this finding to fully understand and then exploit the mechanism of precipitation hardening. This discovery provided aluminum an extra level of strengthening that enabled its alloys to be used in high-strength applications. The growth of the modern aircraft industry would not have been possible without this development. Many high-strength alloys have been developed using this mechanism, which is not only evident in aluminum but also cobalt, nickel, copper and titanium alloys. Two common spring grades of precipitation-hardening stainless steel are 17-7PH and A-286.

In general, the strengthening process is performed in the following three steps:

1. Solution treatment. This process consists of a relatively high-temperature treatment that allows any precipitates and alloying elements to dissolve, or go into a supersaturated "solution." Typical solution heat treatment is done around 1800° to 1950°F for most stainless steels. This treatment can be done during the hot-rolling process and is sometimes referred to as a "Mill Anneal" or "Condition A."

2. Quenching or cooling. After the alloys are brought into solution, the metal is cooled to about room temperature. Cooling can be done in air, oil or water, but must be accomplished fast enough to obtain a supersaturated solid solution. The cooling rate during this operation can be critical to the final performance of the wire. A slow cooling rate from a high temperature tends to produce a coarser grain size than a faster cooling rate from a lower temperature. Material performance can be improved by creating a finer grain size at this point.

3. Precipitation or age hardening. The supersaturated solid solution decomposes with time or temperature as the alloying elements form small precipitate clusters. The formation of these clusters act to significantly strengthen the material. In some alloy systems, these precipitates form at room temperature with the passing of time; this process is then called "natural aging." When heat is used to harden the material, the process is sometimes referred to as "artificial" aging [1].

For stainless steel spring materials, there is an additional hardening step. This occurs between the cooling (step 2) and the precipitation hardening

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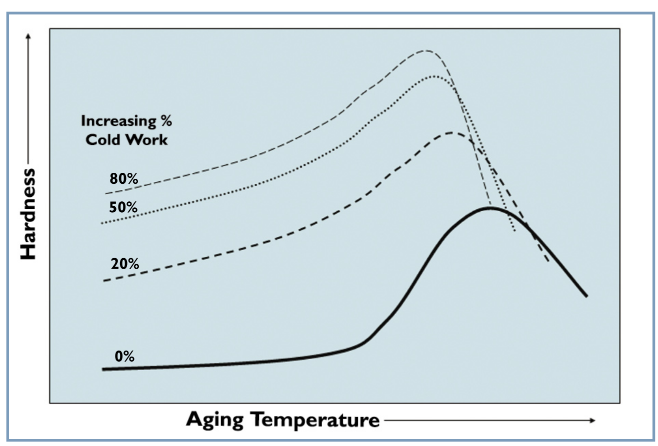

Figure 1: Characteristic relationship between hardness and aging temperature for austenitic PH stainless steel.

(step 3). This step consists of strengthening the steel with enough cold reduction to make the properties that are required by the appropriate specification. As expected, increasing the amount of cold work will cause the final hardness to increase, as seen in Figure 1, page 15. Note that for austenitic stainless steels, as the cold work increases, the optimum aging temperature decreases.

Figure 2, right, shows the relationship between the aging temperature of 17-7PH steel, and the tensile, yield and elongation. As the hardening temperature is increased, the tensile and yield properties increase to a maximum, and then drop off dramatically. As these properties begin to decline with increasing temperature, the elongation starts to increase. This increase in elongation signifies a condition that is called "over-aging." Over-aging occurs as the particles that caused the increase in strength continue to grow in size. As these particles grow, they begin to coarsen and cause a decrease in the hardness with a corresponding increase in elongation.

As the hardness increases during aging, so does the susceptibility to hydrogen embrittlement. Studies of precipitation-hardening stainless steels indicate that material at the peak hardness or slightly over-aged may have enhanced resistance to hydrogen embrittlement [3]. From a material standpoint, being at the peak hardness or to the right of the peak would be better than being under-aged, or to the left of the peak, as the ductility increases when the material becomes over-aged. One exception to this rule is with alloy PH15-7 Mo, where the best combination of strength and elongation is in the under-aged condition [4].

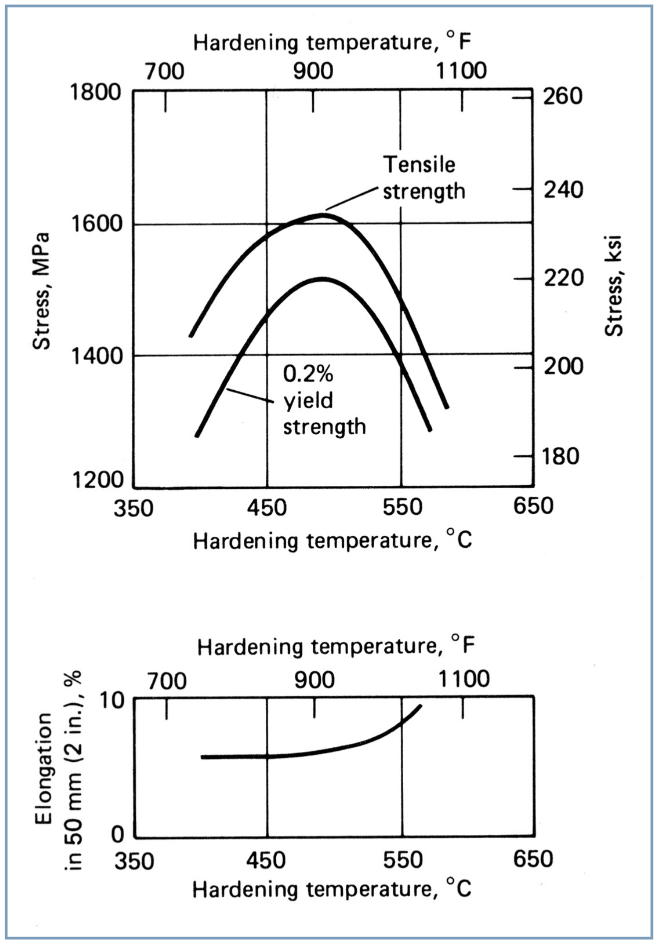

Figure 2: Properties of 17-7PH vs. aging temperature [2].

Stainless Steel Alloys

Most precipitation-hardening stainless steels contain a titanium and/or aluminum addition that forms the fine precipitates responsible for the increase in strength. For example, 17-7PH has about a 1% aluminum addition, and alloy A-286 has a 2% titanium addition. The alloys 17-7PH and A-286 represent the two most popular groups of spring-grade precipitation-hardening stainless steel; semi-austenitic and austenitic, respectively.

Alloy 17-7PH is classified as a semi-austenitic stainless steel because the chemistry is composed so that the microstructure is primarily austenitic at room temperature. Some applications of this grade require refrigeration to -100°F before age hardening. This low-temperature operation is analogous to the cold working done on wire grades, in that both processes transform the microstructure into martensite [4]. The refrigerated and aged condition is identified as the "RH950 condition," and the cold-worked and aged condition is called the "CH900 condition." Note that, in either condition, significant strengthening is obtained from the formation of martensite before aging; therefore it can be expected that this grade is somewhat magnetic. The amount of nickel impacts the transformation to martensite as well as the work-hardening rate on this grade.

Unlike the semi-austenitic precipitation-hardening stainless steels, the austenitic stainless steels cannot be transformed into martensite either by refrigeration or cold work, and they remain virtually non-magnetic even after cold work and aging. Most of these alloys contain a significant amount of nickel (about 26% vs. about 7.5% for the semi-austenitic grades) that prevents the transformation to martensite. The greater alloy content enables the austenitic precipitation-hardening grades to have better corrosion resistance and operate in hotter environments. The precipitation reaction is markedly slower in these alloys, as can be seen in Figure 3, page 16.

The thermal treatment used for precipitation-hardening spring steels not only provides a significant

Precipitation-Hardening Alloys		
	17-7PH	A-286
Nickel Content	6.5 – 7.8%	~26%
Maximum operating temperature	600°F	950°F
Precipitation Treatment	900° for 1 hour	1325° for 16 hours
Magnetic Permeability	>40	~1.007
Rockwell Hardness (in aged condition)	C38 – 57	C35 - 42
Corrosion	General corrosion resistance	Good corrosion resistance

Figure 3: Comparison between the precipitation-hardening alloys 17-7PH and A-286.

increase in strength but also supplies the necessary stress relief. Cold forming after age hardening is generally not recommended, due to the marked increase in strength after hardening. Additional thermal treatments performed after the precipitation hardening may lead to excessive over-aging.

This brief review of the processing of precipitation-hardening stainless steels shows that a balance between alloys, cold work and thermal processing are needed to make a final product that performs optimally after the prescribed age hardening. This balancing act makes these alloys a challenge to produce, but the reward is high-strength steel that can operate in high temperatures yet has a relatively low cost.

References

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