The Heat Treatment of Steel Spring Wire

彈簧鋼線之熱處理

Spring material is often purchased either as pre-hardened wire or in the soft (i.e. annealed) state then heat treated (Fig. 1). This article explores the various heat treatments that are performed on both types and considers the properties of interest that may result.

by Daniel H. Herring

Fig. 1 Spring Wire Forms

Types of Heat Treatments

Stress Relief

Heating pre-hardened steel wire typically into the temperature range of 150℃ – 455℃ (300˚F – 850˚F) followed by a slow cool (<22℃/h or 40˚F/hour) operation will relieve internal (residual) stress in the material as well as improve dimensional stability and increase the yield strength of cold drawn wire. Hydrogen embrittlement due to plating operations can be negated by stress relief provided that the soak times are increased **(Table 2)**.

The results of the stress relieving process are dependent on the temperature and time which are expressed by either the Holloman-Jaffe parameter, which is a measure of the thermal effect of the process or the Larson-Miller equation (Equation 1).

(1) P = T (C + log t) X 10-3

Where is the time (in hours) at temperature T (in "K") and the value for the composition dependent constant C is calculated from a separate equation (Equation 2).

(2) C = 21.3 – (5.8 x % carbon in the steel)

Table 1. **Typical Stress Relief Temperatures and Times for Steel Wire**

Material	Specifications	Temperature°C (°F)	Time (minutes)
Music Wire	ASTM A 228	232 (450)	30
Music Wire (tin coated)	ASTM A 228	150 (300)	30
Music Wire (cadmium-zinc) coated	ASTM A 228	204 (400)	30
Music Wire	AMS 5112	282 (540)	60
O.T.M.B.	ASTM A 229	232 (450)	30
H.D.M.B. Class I or II	ASTM A 227	232 (450)	30
High Tensile Hard Draw	ASTM A 679	232 (450)	30
Galvanized M. B. Class I or II	ASTM A 674	232 (450)	30
Chrome-Silicon	ASTM A 401 (SAE J157)	371 (700)	60
Chrome-Silicon (Lifens)	SAE J157	385 (725)	60
Chrome-Vanadium	ASTM A 231	371 (700)	60
301 Stainless Steel	-	343 (650)	30
302 Stainless Steel	AMS 5688	343 (650)	30
304 Stainless Steel	ASTM A 313	343 (650)	30
316 Stainless Steel	ASTM A 313	315 (600)	60
17-4 PH Stainless Steel	AMS 5678	482 (900)	60
Phosphorus Bronze Grade A	ASTM B 159	190 (375)	30
Hastelloy C	-	260 (500)	30
Monel 400	-	329 (625)	60
Inconel 600	-	454 (850)	90
Inconel X700 Spring Temper	AMS 5699	650 (1200)	240
Inconel X750 (1 Temper)	AMS 5698	-	-
Brass Wire	ASTM B 134	190 (375)	30
Beryllium Copper	ASTM B 134 (ASTM B 197)	315 (600)	120
Blue-Temper	-	232 (450)	30

As an example, when wire is coiled into a compression spring, the steel on the inside of the coil is upset and becomes shorter (due to plastic deformation and the residual stresses on the inside of the spring) thus reducing the fatigue strength. Stress relief can be used to help negate these residual stresses.

The magnitude of the residual stresses that are formed is dependent on the tensile strength of the steel wire. The amount of stress relief after coiling is a function of temperature for a CrV and CrSi wire. Typically, the CrSi wire exhibited approximately 40% greater residual stresses than the CrV wire. The residual stress is a function of distance from the surface for CrV and CrSi wire after stress relieving **(Fig. 2)**. In addition,

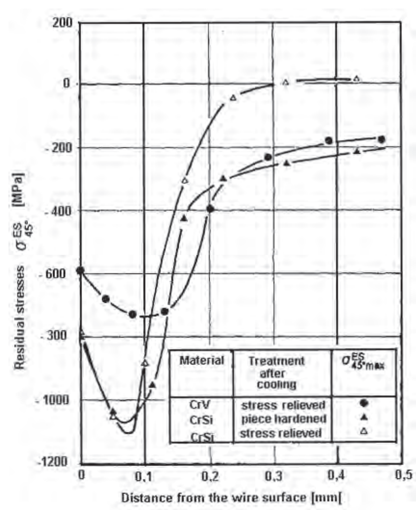


Figure 2.
Residual Stress in Valve Springs of CrV and CrSi Wire
Subject to Different Heat Treatments

Table 2. **Hydrogen Bake Out Requirements for High Strength Parts**

Tensile Strength		Hardness (HRC)	Time (hrs) Post Plate Bake Out at 375°- 430°F (190°C - 220°C)
MPa	ksi		
1700 – 1800	247 – 261	49 – 51	22+
1600 – 1700	232 – 247	47 - 49	20+
1500 – 1600	218 – 232	45 - 47	18+
1400 – 1500	203 – 218	43 - 45	16+
1300 – 1400	189 – 203	39 – 43	14+
1200 – 1300	174 – 189	36 – 39	12+
1100 – 1200	160 – 174	33 – 36	10+
1000 – 1100	145 -160	31 – 33	8+

Notes: per ASTM B 850-98 (2004)

Figure 3.
Tensile Strength versus Hardness –
Hardened & Tempered Spring Steel

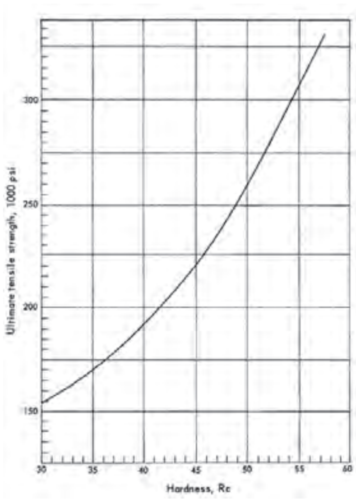
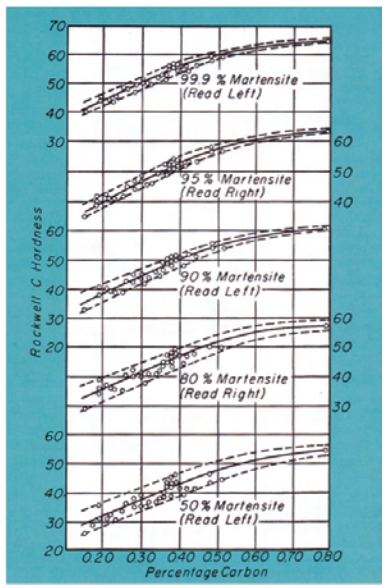


Figure 4.
Percentage Martensite as a Function of
Carbon Content and Hardness



it was reported that the negative effects of residual stresses due to coiling were eliminated; increased residual tensile stresses resulted in improved fatigue strength.

Hardening

Austenitizing followed by quenching and tempering is used on a variety of high carbon steels and high carbon alloy steels to develop higher hardness **(Fig. 3)**. The spring steel is heated above the materials upper critical temperature (Ac3) so that the crystal structure will convert to austenite (-iron). The wire must be held at this temperature long enough for the structure to completely transform, approximately 72 seconds for each 1 mm (0.040") of thickness in a furnace or 30 seconds in a salt or lead bath. Quenching can be done in air, oil, polymer or water but must be rapid enough to form the maximum amount of martensite for the carbon level present with a minimal amount of retained austenite **(Fig. 4)**.

A high magnitude of internal stress may develop when steel is cooled rapidly, or is severely cold worked. This stress can be high enough to cause the steel to crack or break spontaneously, or at least to warp or distort. Tempering is used to reduce hardness, improve toughness and ductility and improve dimensional stability. During tempering, the microstructure changes (carbide decomposition and the martensite alters somewhat) allowing hardness (strength) to decrease and ductility to increase.

Properties of Metals

Understanding the various properties that can be achieved in spring wire is another important issue. Knowledge and understanding of the uses, strengths, limitations, and other characteristics of the material is vital to properly application. The use of unsuitable materials can readily erase the finest craftsmanship. The various concepts can be explained as follows:

Hardness

Hardness refers to the ability of a material to resist abrasion, penetration, cutting action, or permanent distortion. Hardness may be increased by cold working and, in the case of steel, by heat treatment. The ability of the material to resist plastic deformation depends on the carbon content and microstructure of the steel. Therefore, the same steel can exhibit different hardness values depending on its microstructure, which is influenced by the cooling (transformation) rate. Hardness and strength are closely associated properties of metals.

Hardenability

Hardenability describes the heat treatment response of steels using either the concepts of hardness or microstructure. In contrast to hardness, hardenability is a material property, independent of cooling rate and dependent only on chemical composition and grain size. When evaluated by hardness testing, hardenability is defined as the capacity of the material under a given set of heat treatment conditions to harden "in depth". In other words, hardenability is concerned with the "depth of hardening" or the hardness profile obtained, not the ability to achieve a particular hardness value. When evaluated by microstructural techniques, hardenability is defined as the capacity of the steel to transform partially or completely from austenite to some percentage of martensite at a given depth when cooled under known conditions.

Strength

One of the most important properties of a material is strength. Strength is the ability of a material to resist an applied force that would create deformation of the material. Strength is also the ability of a material to resist stress without breaking. The type of load or stress on the material affects the strength it exhibits.

Ductility

Ductility is the property of a metal that permits it to be permanently drawn, bent, or twisted into various shapes without breaking. This property is essential for metals used in making wire and tubing. Ductile metals are greatly preferred because of their ease of forming and resistance to failure under shock loads. Ductility is similar to malleability.

Toughness

A material that possesses toughness will withstand tearing or shearing and may be stretched or otherwise deformed without breaking. Toughness is a desirable property in any application involving shock loading or sudden impact. Toughness will vary as a function of the temperature at which the material is exposed.

Elasticity

Elasticity is that property that enables a metal to return to its original size and shape when the force that causes the change of shape is removed. This property is extremely valuable because it would be highly undesirable to have a part permanently distorted after an applied load was removed. Each metal has a point known as the elastic limit, beyond which it cannot be loaded without causing permanent distortion. This property is highly desirable in spring steel.

Brittleness

Brittleness is the property of a metal that allows little bending or deformation without shattering. A brittle metal is apt to break or crack without change of shape. Because structural metals are often subjected to shock loads, brittleness is not a very desirable property.

Conductivity

Conductivity is the property that enables a metal to carry heat or electricity. The heat conductivity of a metal is especially important in welding because it governs the amount of heat that will be required for proper fusion. Conductivity of the metal, to a certain extent, determines the type of jig to be used to control expansion and contraction.

Thermal Expansion

Thermal expansion refers to contraction and expansion that are reactions produced in metals as the result of heating or cooling. Heat applied to a metal will cause it to expand or become larger. Cooling and heating affect the allowable design tolerances.

In Conclusion

The proper heat treatment of a spring wire is one of the most important aspects of its successful application. In order to predict how the part will behave, it is important to know both the type of properties desired and the response of the material to either stress relief or hardening.

References

1. *Master Spring and Wire Form Company (www.masterspring.com)*
2. *Canale, Lauralice C. F., George E. Totten, Antonio C. Canale, and Maria Regina Gasparini, Overview of Factors Contributing to Steel Spring Performance and Failure, Int. J. Microstructure and Materials Properties 2007, Vol. 2 No. ¾, pp. 262 – 309.*
3. *Herring, D. H., Bake Out Cycle After Plating, The Experts Speak Blog, Industrial Heating (www.industrialheating.com), in preparation.*
4. *Spring Steel Types Used in Spring Making (www.spring-makers-resource.net)*
5. *Herring, D. H., H-Band and RH-Band Steels, Industrial Heating, March 2009.*
6. *McKenna, Patrick, D.H. Herring and Craig Darragh, How to Communicate Heat Treating Requirements to Your Heat Treater, Industrial Heating, May 2010.*