应力的消除 Stress Relief

By Daniel H. Herring

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Processes which depend on slow cooling (e.g. annealing, normalizing, stress relief) do so for a number of reasons; to relieve stresses, improve chemical homogeneity, soften a material for subsequent operations (e.g. machining), refine grain size and for such reasons as embrittlement relief or magnetic properties[1]. As a general rule, the larger or more complex the part, the greater the amount of internal stress present.

Stress relief can be differentiated from other slow cooling processes in that it is most often performed below the lower critical temperature (Ac1). Time at temperature depends on such factors as the complexity of the part and enough time must be allowed in order to achieve the desired reduction in residual stress level. Following stress relief, the steel is cooled at a sufficiently slow rate to avoid formation of or reintroduction of excessive thermal stresses. No microstructural phase changes occur during the stress relief process.

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For stainless steels the situation is more complex[2]. Stress relief is done in the range of 290℃ - 425℃ (550℉ - 800℃), which is below the sensitization range. The operation depends on the form of the material, the operation being performed (e.g. machining) or if a completed assembly is to have a stress relief performed on it.

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Poor Man's Stress Relief

In hardening, rapid cooling/quenching alone or in combination with pre-existing internal stresses can result in unwanted distortion, brittle fracture, and if near welds in certain grades of metal, stress corrosion cracking. For this reason a number of heat treaters introduce a "stress relief hold" during hardening or case hardening treatments. This involves heating of a workload to an intermediate temperature, in the range of 538℃ (1000℉)-705℃ (1300℉) and soaking for a period of time equivalent to one (1) hour per 25 mm (1 inch) of maximum cross sectional area. The idea is to allow for stress relaxation so that more predictable dimensional change occurs on quenching.

品质不佳的应力消除

在硬化程序中，快速的冷却／淬火以及材料内本身存在的内部应力可能造成结构上的瑕疵、脆性断裂或特定金属在焊接点附近的慢性应力裂痕。因此，许多热处理者会在硬化程序或参碳淬火程序中加入一个「应力消除等待」步骤，亦即将标的物加温至538℃(1000℉)-705℃(1300℉)的过渡性温度后浸泡一段时间，而该浸泡时间系以最大横切面每25mm（1英吋）增加一小时的方式计算。该操作的目的是为了让应力减缓，以增加淬火过程中尺寸变化的可预测性。

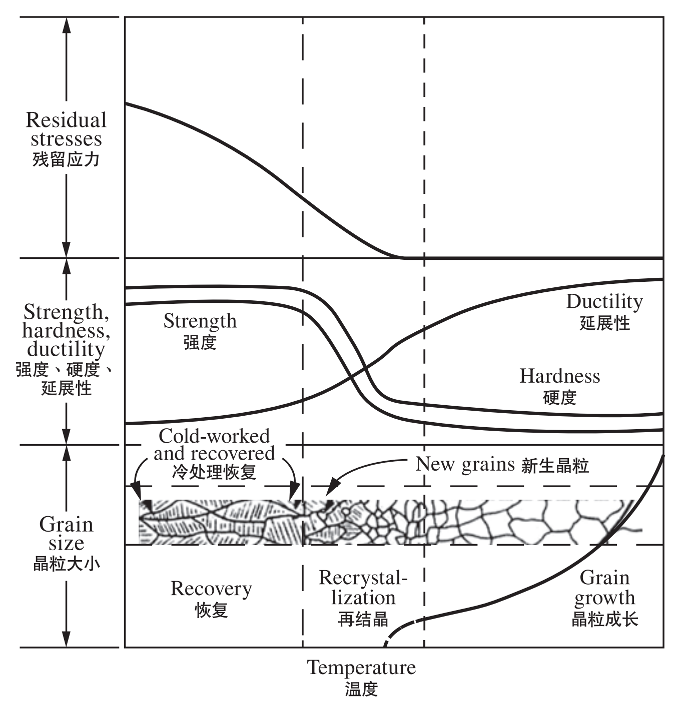
Stress Relief of Springs

Stress relief is one of the most common heat-treating processes used in spring manufacturing as well as the manufacture of other wire formed products. Drawing, forming and machining induce stresses in all fastener and other wire products. These stresses can cause loss of tolerance, cracking and distortion and contribute to in service failures. For these reasons stress relieving is often necessary and in many cases, mandatory.

In addition to removing stresses, stress relief returns the material to a strength level approximately equivalent to where it was prior to forming. Studies have shown[3] that the interstitial elements pin the lattice defects in the atomic structure of the metal, resulting in this increase in mechanical strength.

To completely eliminate residual stresses in helical springs, for example, the material must be heated high enough to fully recrystallize. This is not practical in spring manufacturing since the recrystallization process significantly reduces the material's strength and, therefore, its usefulness in spring applications. On the other hand, an elevated temperature recovery process (i.e. stress relief) can eliminate the majority of residual stresses without significantly deteriorating the material's strength **(Fig. 1)**. The temperature required to accomplish the recovery process depends on the material type and processing history (i.e. carbon steel vs. alloy steel, cold drawn vs. oil tempered, etc.) The SMI Encyclopedia of Spring Design[4] provides recommendations for proper recovery.

Figure 1 Effects of Recovery and Recrystallization on Grain Structure
图1. 恢复与再结晶对晶粒结构的影响



弹簧的应力消除

应力消除为弹簧制造以及线材产品制造过程中最常见的热处理程序之一。抽线、成形与机器加工会在扣件以及线材产品中产生应力。该应力可能进一步造成疲乏、龟裂、变形或材料功能失效。因此，应力消除不但有其必要性，往往还是强制要求的处理程序之一。

除了应力的移除外，应力消除程序还可以将材料回复到与其成形前相近的强度。研究显示[3]，间.隙元素会将金属原子结构中的晶格缺陷定住，使其机械强度增强。

例如，如果要完全消除螺旋弹簧中的残余应力，目标材料必须加热至足以充分再结晶之温度。这在弹簧制造过程中是无法做到的，因为再结晶的过程会严重降低材料的强度，使得该材料的实用性大受影响。另一方面，高温下的恢复过程（亦即应力消除过程）可以消除大部分的残留应力，且不会严重降低材料的强度（**图1**）。恢复程序所需到达的温度取决于材料的种类以及加工历史（亦即碳钢或合金钢、冷抽或由回火等等）。SMI Encyclopedia of Spring Design[4] 中提供了如何进行正却恢复的建议。

Temperature, time, and time at temperature are key process variables and these have been documented elsewhere[5]. In general, heating steel to a temperature of about 75℃ (165℉) below the transformation temperature (Ac1) for about one (1) hour (or until the entire part reaches the temperature), will allow for the removal of most internal stresses. Typical temperature ranges are:

- 550℃-650℃ (1025℉-1200℉) for unalloyed and low-alloy steels
- 600℃-700℃ (1115℉-1300℉) for hot-work and high-speed tool steels.

The results of the stress relieving process 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 t 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)

For many alloy steels little or no stress relief occurs at temperatures less than approximately 260℃ (500℉) while approximately 90% of the stress is relieved by 540℃ (1000℉). The maximum temperature for stress relief is limited to 30℃ (55℉) below the tempering temperature used after quenching from the hardening process. After removing from the furnace or oven, the wire must be cooled in still air. If cooled in any other manner, stresses are reintroduced into the part.

Many other severely cold worked or bent shapes can be heated between 205℃ (400℉) - 425℃ (800℉) for a relatively short time to help reduce internal stresses. Alternative stress relief processes (e.g. vibratory stress relief, rapid tempering/stress relief) are covered in the references[6],[7],[8].

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 reduce the fatigue strength. Stress relief can be used to reduce 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 as 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 as function of distance from the surface for CrV and CrSi wire after stress relieving (**Fig. 2**). In addition, it was reported that the negative effects of residual stresses due to coiling were eliminated; increased residual tensile stresses resulted in improved fatigue strength.

温度、时间与在某温度下的时间长度为关键的制程变量，且这些因素已于它处有了记载[5]。一般来说，将钢加热到低于转换温度(Ac1)约75℃ (165℉)大约一个小时（或者直到整个部件到达正确的温度），将可以消除大部分的内部应力。常见的温度范围为：

•非合金与低合金钢材：550℃-650℃(1025℉-1200℉)

•热作与高速工具用钢材：600℃-700℃(1115℉-1300℉)。

应力消除的结果可用Holloman-Jaffe参数或Larson-Miller等式（等式1）来表达。Holloman-Jaffe参数为制程中的热效应之表示。

(1) $P = T (C + \log t) X 10^{-3}$

其中 t 为在温度 T （以 K 为单位）下的时间（以小时为单位）。与内含物相关的常数 C 系由另一个等式作计算（等式2）。

(2) C = 21.3 – (5.8 x 钢中的碳%)

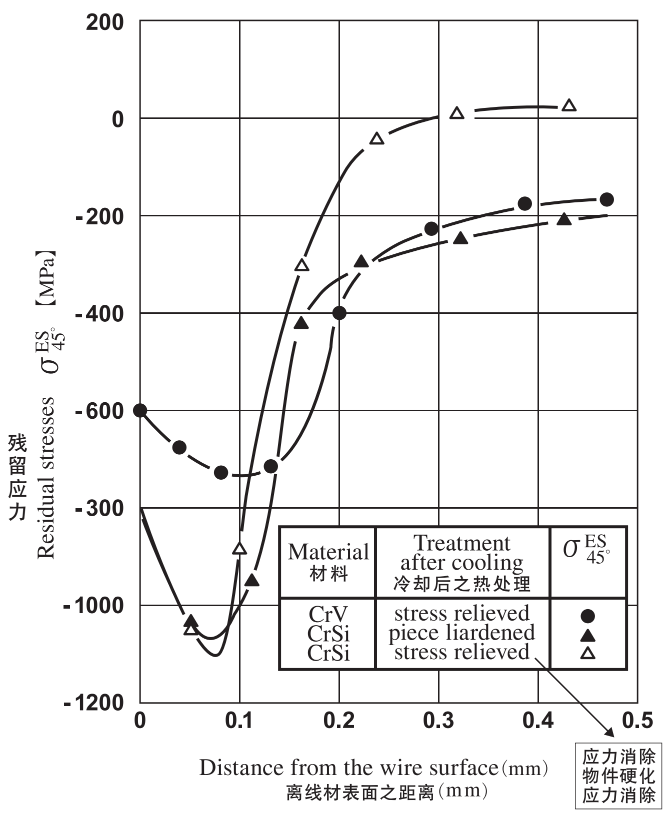
对于许多种合金来说，当温度低于260℃ (500℉)时，不会有任何的应力消除发生；当温度到达540℃ (1000℉)，有90%的应力会被消除。应力消除的最大温度为低于硬化过程中淬火后所使用的回火温度30℃ (55℉)。从火炉或烤箱取出后，线材必须在静止的空气中冷却。若用它种方式冷却，将会在部件中再度产生应力。

许多其它重度冷处理过或弯曲过的材料可以短时间加热至205℃-425℃(400℉-800℉)之间以帮助减轻内部应力。参考文件[6],[7],[8]中记载了其它应力消除的程序方法（例如：振动应力消除法、快速回火／应力消除法）。

举例而言，当线材被盘绕成为压缩弹簧，线圈内部的钢材因为塑性变形而变短，而弹簧内部的残余应力会使得疲乏强度降低。应力消除可用以降低这类残余应力。所形成的残余应力大小取决于钢质线材的拉伸强度。冷却后的应力消除程度对CrV与CrSi线材来说为温度的函数。一般而言，CrSi线材的残余应力比CrV线材要高出约40%。应力消除后的CrV与CrSi线材，其残余应力为离表面之距离的函数（**图2**）。另外，研究显示因为压缩卷曲所产生的残余应力所造成的负面效应消除了，而且残余拉伸应力的增加更改善了疲乏强度。

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

图2. 不同热处理下的阀门弹簧CrV与CrSi 线材中的残余应力



The influence of internal stress can be positive or negative, which means that one must understand the design application in order to apply the proper stress relief operation (at low or high temperature). In lightly stressed parts where dimensional tolerances are not critical, the presence of internal stress is not as great a concern as a highly stressed component that must hold dimensional stability over time or where the service application is such that excessive distortion or even fracture may occur.

结论

内部应力的影响可能是正面的也可能是负面的，因此我们必须先了解应用的设计才能知道该使用何种应力消除方法（高温或低温）。在只有轻度应力存在的部件或结构性弹性不是绝对重要的部件中，内部应力的存在与否并不需要受到太大的关注。但是在存在高度应力的部件、必须长期维持结构性稳定的部件以及过度变形甚至断裂可能发生的应用中，内部应力的存在与否便是一个极重要的课题。

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