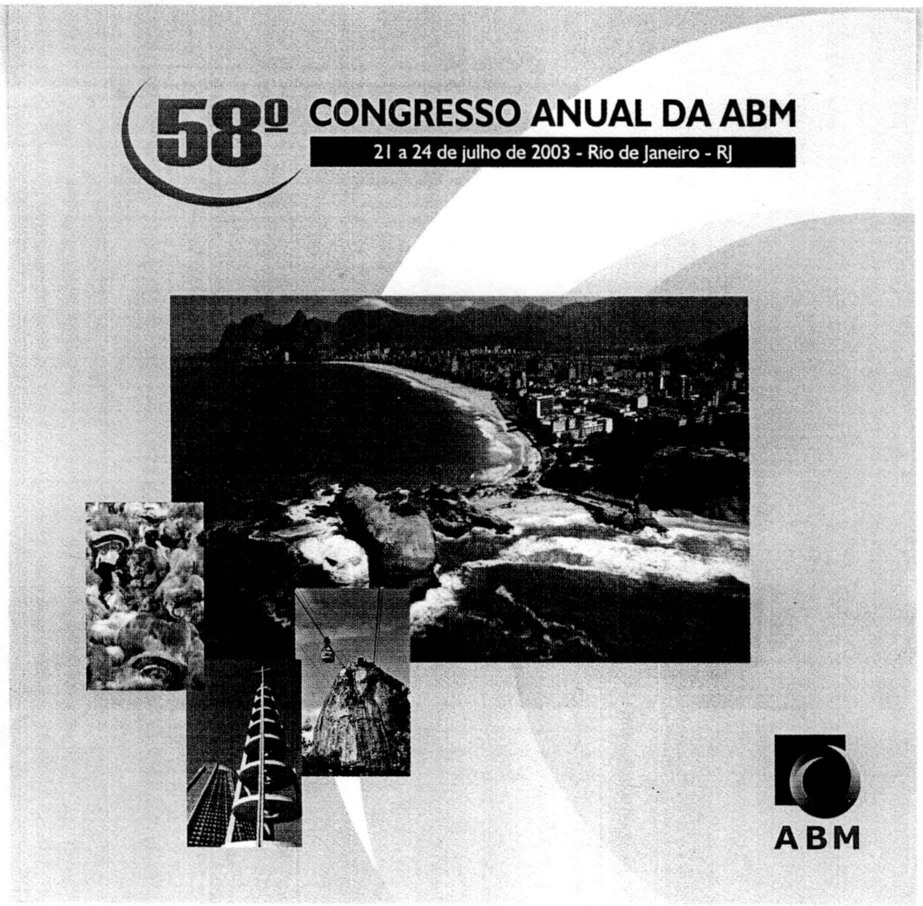

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RAPID TEMPERING AND STRESS RELIEF: APPLICATION OF HIGH SPEED CONVECTION HEATING[1]

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Abstract

Although rapid stress-relieving and rapid tempering are well known processes, such as salt bath processing and particularly induction tempering, these terms are rarely used in conjunction with processes conducted in a convection oven. However, rapid heating technology has been developed for convection ovens where the use of a proprietary high-speed convection oven with turbulent flow is used to achieve not only faster processing times but improved quality and properties are obtained as well. In this paper, an fundamental overview of stress relieving and tempering and the development and use of proprietary rapid-heating technology for stress relieving and tempering operations will be provided. Selected applications related to the production of automotive components will also be discussed.

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Introduction

Rapid heating is defined as "any heating method that accelerates conventional furnace heating" [1]. Heat transfer rates of up to thirty (30) times those achieved in conventional convection furnaces are possible [2]. In the past rapid heating technology has been applied primarily to the forging industry where steel is heated to 1000 – 1250ºC (1830 – 2280°F) and it is much less commonly encountered in the heat treating industry.

Although rapid heating is enjoying increasing use in for stress relieving, the use of rapid heating technology is still in its infancy for tempering processes. In this paper a brief overview of stress relieving and tempering will be provided; high-speed convection and temperature uniformity will be addressed, use of a laboratory batch oven to model in-line continuous oven heating (and cooling) will be discussed and finally selected examples will be provided.

Discussion

The Stress Relieving Process

Stress relieving is typically used to remove residual stresses which have accumulated from prior manufacturing processes. Stress relief is performed by heating to a temperature below Ac1 (for ferritic steels) and holding at that temperature for the required time to achieve the desired reduction in residual stresses and then the steel is cooled at a rate to sufficiently slow avoid formation of excessive thermal stresses. No microstructural changes occur during stress relief processing. Nayar recommends heating to [3]:

- 550-650°C for unalloyed and low-alloy steels;
- 600-700°C for hot-work and high-speed tool steels.

These temperatures are above the recrystallization temperatures of these types of steels. Little or no stress relief occurs at temperatures < 260°C and approximately 90% of the stress is relieved at 540°C. The maximum temperature for stress relief is limited to 30°C below the tempering temperature used after quenching [4].Stress relieving results in a significant reduction of yield strength in addition to reducing the residual stresses to some "safe" value and crack-sensitive materials. Typically, stress-relieving times for specific alloys are obtained from standards such as those listed in Table 1 [5-7]. The stress-relieving times shown in Table I were developed for conventional convection heated batch oven. With rapid stress-relieving technology the total stress relieving time for 16 mm diameter CrSi wire can be reduced to 10 min. or less.

The results of the stress relieving process are dependent on the temperature and time which are correlated through Holloman's parameter (P) [8]:

$$P = T\,(C + \log t)$$

Where T is the temperature in K, t is the time (h) and C is the Holloman-Jaffe constant which is calculated from:

$$C = 21.53 - (5.8 \times \%C)$$

P is a measure of the "thermal effect" of the process and that processes with the same Holloman's parameter exhibit the same effect. Another similar commonly used expression used in evaluating the stress relief of spring steels is the Larson-Miller equation [5-7,9]:

$$P = T (\log t + 20) / 1000$$

Software (Pyromaitre's Pyrograph) has been developed which has utilized the use of the Larson-Miller equation to model production heating requirements for high-speed stress-relieving oven selection. A typical example of the output is shown in Figure 1.

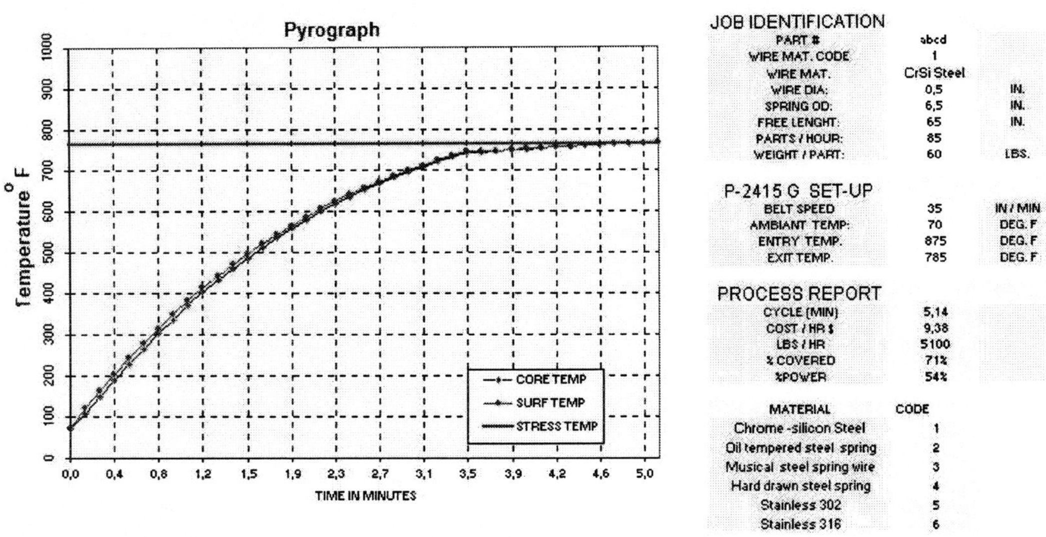

Figure 1 – Illustration of the pyrograph image showing both the input parameter menu and the graphical output.

Tempering

When steel is hardened, the as-quenched martensite is not only very hard but also brittle. Tempering, also known as "drawing", is the thermal treatment of hardened and normalized steels to obtain the desired mechanical properties which include: improved toughness and ductility, lower hardness and improved dimensional stability. During tempering, as-quenched martensite is transformed into tempered martensite which is composed of highly dispersed spheroids of cementite (carbides) dispersed in a soft matrix of ferrite resulting in reduced hardness and increased toughness. The objective is to allow hardness to decrease to the desired level and then to stop the carbide decomposition by cooling. The extent of the tempering effect is determined by the temperature and time of the process [10,11].

Table 1
Standard Stress Relief Temperatures and Times for Wire

Material	Specifications	Temperature (°F)	Time (Minutes)
Music Wire	ASTM A 228	450	30
Music Wire – tin-coated	ASTM A 228	300	30
Music Wire Cadmium-Zinc Coated	ASTM A 228	400	30
Music Wire	AMS 5112	540	60
O.T.M.B.	ASTM A 229	450	30
H.D.M.B. Class I or II	ASTM A 227	450	30
High Tensile Hard Draw	ASTM A 679	450	30
Galvanized M.B. Class i or ii	ASTM A 674	450	30
Chrome-Silicon	SAE J157 or ASTM A 401	700	60
Chrome-Silicon (Lifens)	SAE J157	725	60
Chrome-Vanadium	ASTM A 231	700	60
Stainless Steel 301	----	650	30
Stainless Steel 302	AMS 5688	650	30
Stainless Steel 304	ASTM A 313	650	30
Stainless Steel 316	ASTM A 313	600	60
17-7 PH	AMS 5678	900	60
Phosphorous Bronze Grade A	ASTM B 159	375	30
Hasteloy C	----	500	30
Monel 400	----	625	60
Inconel 600	----	850	90
Inconel X 700 Spring Temper	AMS 5699	1200	240
Inconel X 750 /1 Temper	AMS 5698	----	----
Brass Wire	ASTM B 134	375	30
Berilium-Copper	ASTM B 134 or ASTM B 197	600	120
Blue-Temper	N/A	450	30

The tempering process involves heating hardened steel to some temperature below the eutectoid temperature for the purposes of decreasing hardness and increasing toughness [12]. (Tempering is performed as soon as possible after it has cooled to between 50°-75°C and room temperature to reduce the potential of cracking. If a tool steel cannot be tempered immediately after quenching, it is recommended that it be held at 50°C - 100°C in an oven until it can be tempered [13].)

The tempering process may be conducted at any temperature up to the lower critical temperature (A_{c1}). Figure 2 illustrates the effect of carbon content and tempering temperature on hardness of carbon steels [11]. The specific tempering conditions that are selected are dependant on the desired strength and toughness. Nayar has recommended the following tempering conditions [3]:

- Heat the parts to 150-200°C to reduce internal stresses, increase toughness without a significant loss in hardness. This is often done with surface-hardened parts.
- To obtain the highest attainable elastic limit and sufficient toughness, temper at 350-500°C.
- For optimum strength and toughness, heat to 500-700°C. (Note: When tempering at high temperatures, 675°C - 705°C, precautions must be taken not to exceed the A_{c1} temperature, above which undesirable austenite may be formed which upon cooling would transform to pearlite. This is a particular concern for nickel-containing steels since nickel depresses the A_{c1} temperature.)

In some cases, a "refrigeration" or "sub-zero" treatment is performed on steels to transform retained austenite to as-quenched martensite. Conversion of retained austenite in this way results in improved hardness, wear resistance and dimensional stability. Sub-zero treatment is performed using dry-ice or liquid nitrogen and involves cooling the steel to a temperature less than the M_f temperature of the steels which is typically between -30°C -70°C. (Tool steels will grow between about 0.0005 – 0,002 inches per inch of original length during heat treatment [13].) An immediate tempering step is required to remove residual stresses imparted to the steel by this process. Sub-zero treatments are not effective on steels that have been held at room temperature for several hours and therefore it is typically performed immediately after hardening. Although the general rule is to allow one hour per inch of the thickest cross-section, tool steels should be held at temperature for a minimum of two hours for each temper [13].

Martensitic stainless steels and alloy steels that contain > 0.4% carbon and which exhibit M_S temperatures of about 300°C are particularly susceptible to cracking, especially if they are through-hardened [4]. In such cases, cooling may be interrupted at about 80°C followed by an immediate temper at about 170°C to stop the formation of martensite. However, significant amounts of untempered martensite remain after the steel is cooled to room temperature. Therefore, the steel must be tempered a second time at the same temperature to transform the hard and brittle as-quenched martensite to a softer and more ductile tempered martensite. This is one form of a "double tempering" process.

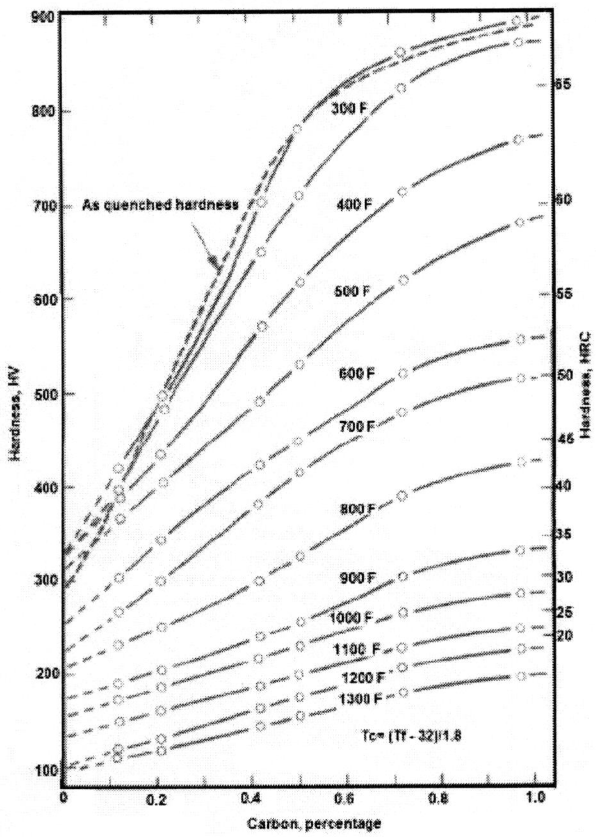

Figure 2 - Correlation of carbon content of martensite and hardness of different Fe-C alloys at different tempering temperatures.

Another form of double tempering occurs for high-alloy chrome steels and high-speed tool steels where significant amounts of retained austenite is transformed to martensite after tempering at about 500°C. Such steels should be retempered to obtain a tougher martensitic structure. Generally, this second tempering step is performed at about 10°C - 30°C below the original tempering temperature [4].

Steels that exhibit a high M_S temperature,   400°C, typically those that contain < 0.3% carbon, form martensite which may be tempered during the remaining cooling (quenching) process. This is called "self-tempering" or "auto-tempering" and such steels are typically not crack-sensitive, particularly if the M_f temperature is   100°C [4].

Typically, tempering times are a minimum of approximately one hour. Thelning has reported a "rule of thumb" of 1-2 hours/inch of section thickness after the load has reached a preset temperature [4]. After heating, the steel is cooled to room temperature in still air. The recommended tempering conditions, in addition to recommended heat treating cycles, for a wide range of carbon and alloy steels is provided in SAE AMS 2759.

Tempering times and temperatures may also be calculated by various methods. One of the more common methods is to use the Larsen Miller equation discussed above. The Larsen-Miller equation, although originally developed for prediction of creep data, has been used successfully for predicting the tempering effect of medium/high alloy steels [14]. Bofors [4] reported that a Holloman-Jaffe constant (C = 20) was appropriate for all steels but Grange and Baughman reported that C = 18 should be used [9].

Sinha showed in Figure 3a that the Holloman-Jaffe constant varies with carbon content and desired hardness [9]. The incremental contribution to hardness of each alloying element of a steel may be determined from Table 2 [4]. The hardness (DPH) is calculated by multiplying the concentration of each of the alloying elements (within the range shown) times the factor for that element at a given constant (C) and then all of these values are added together to provide the hardness (DPH). The interrelationship between tempering time and the Holloman-Jaffe parameter (P) at different tempering temperatures is shown in Figure 3b [9].

The interrelationship between tempering temperature, time and steel chemistry has been reported by Spies [8,15]:

$$HB = 2.84H_h + 75(\%C) - 0.78(\%Si) + 14.24(\%Mn) + 14.77(\%Cr) + 128.22(\%Mo) - 54.0(\%V) - 0.55T_t + 435.66$$

Table 2
Factors for Predicting the Hardness of Tempered Martensite

Element	Range (%)	Factors at Indicated Parameter (C) Value[2]					
		20	**22**	**24**	**26**	**28**	**30**
Mn	0.85-2.1	35	25	30	30	30	25
Si	0.3 – 2.2	65	60	30	30	30	30
Ni	4	5	3	6	8	8	6
Cr	1.2	50	55	55	55	55	55
Mo	0.35	40	90	160	220	240	210
		(20)[1]	(45)[1]	(80)[1]	(110)[1]	(120)[1]	(105)[1]
V[3]	0.2	0	30	85	150	210	150

1. If 0.5 – 1.2 % Cr is present use this factor
2. Note: The Boron factor is 0.
3. May not apply if vanadium is the only carbide former present.

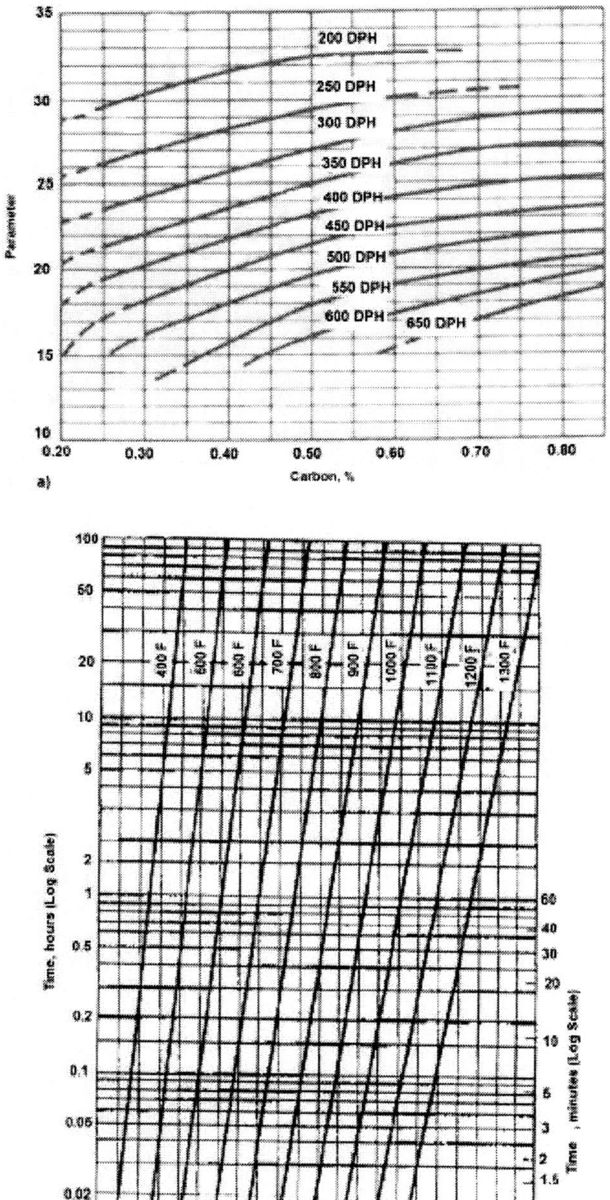

Figure 3 – a.) Variation of the Holloman Parameter (P) at different hardness levels.; b.) Time-temperature versus Holloman Parameter chart for C = 18.

where: HB is the Brinell hardness after hardening and tempering, H_h is the Rockwell (HRc) hardness after hardening, and T_t is the tempering temperature in °C. This equation was developed for the following conditions:

H_h = 20-65HRc, C = 0.20-0.54%, Si = 0.17-1.40%, Mn = 0.50-1.90%, Cr = 0.03-1.20% and T_t = 500-650°C (932-1202°F).

High Speed Convection

Tempering may be performed in convection furnaces, salt baths or even by immersion in molten metal. Induction tempering and flame heating are also used but will not be discussed further here. Of the different tempering systems shown, convection furnaces are the most common and it is important that they be equipped with fans and/or blowers to provide for uniform heat transfer when heating the load. Typically, convection tempering furnaces are designed for use within 150°C - 750°C.

One of the most important and critical deficiencies of most conventional stress-relieving and tempering ovens is the actual temperature non-uniformity of the material being heated. This is illustrated in Figure 4 where it is shown that the actual temperature of the part depends on its placement in the basket in the oven. A high-precision oven requires not only uniform temperature but uniform heat transfer. Rapid heat transfer is achieved by the use of turbines. However, this is not sufficient for uniform heat transfer which is achieved by the number of turbines used and their position, the shape of the heating chamber, and placement of the component on the belt to optimize surrounding air flow. Therefore, both the heating velocity and temperature uniformity of the part is optimized.

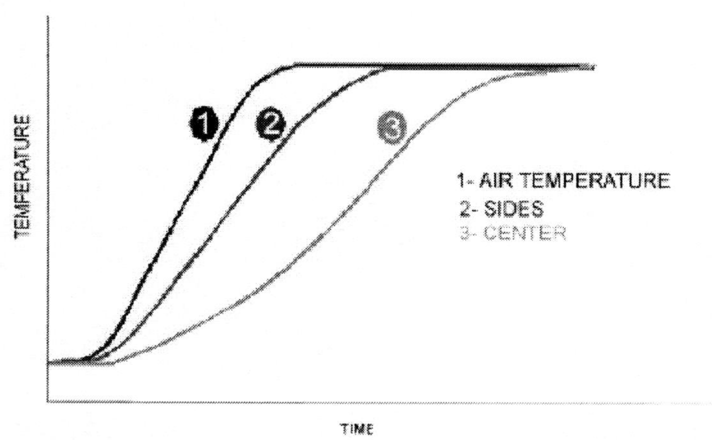

Figure 4 – Illustration of temperature non-uniformity typically present in conventional batch ovens.

It is important to note that optimal stress relief for a given material is not a fixed value of one specific time and one specific temperature as suggested in Table 1. This is illustrated by x-ray diffraction data shown in Figures 5a and 5b [5-7]. These data show that five (5) minutes at 800ºF is equivalent to 770°F using a Pyro high-speed stress relief oven. Also ten (10) minutes at 770ºF in the same Pyro high-speed stress-relieving oven is equivalent to 25 minutes in a conventional batch oven at the same temperature.

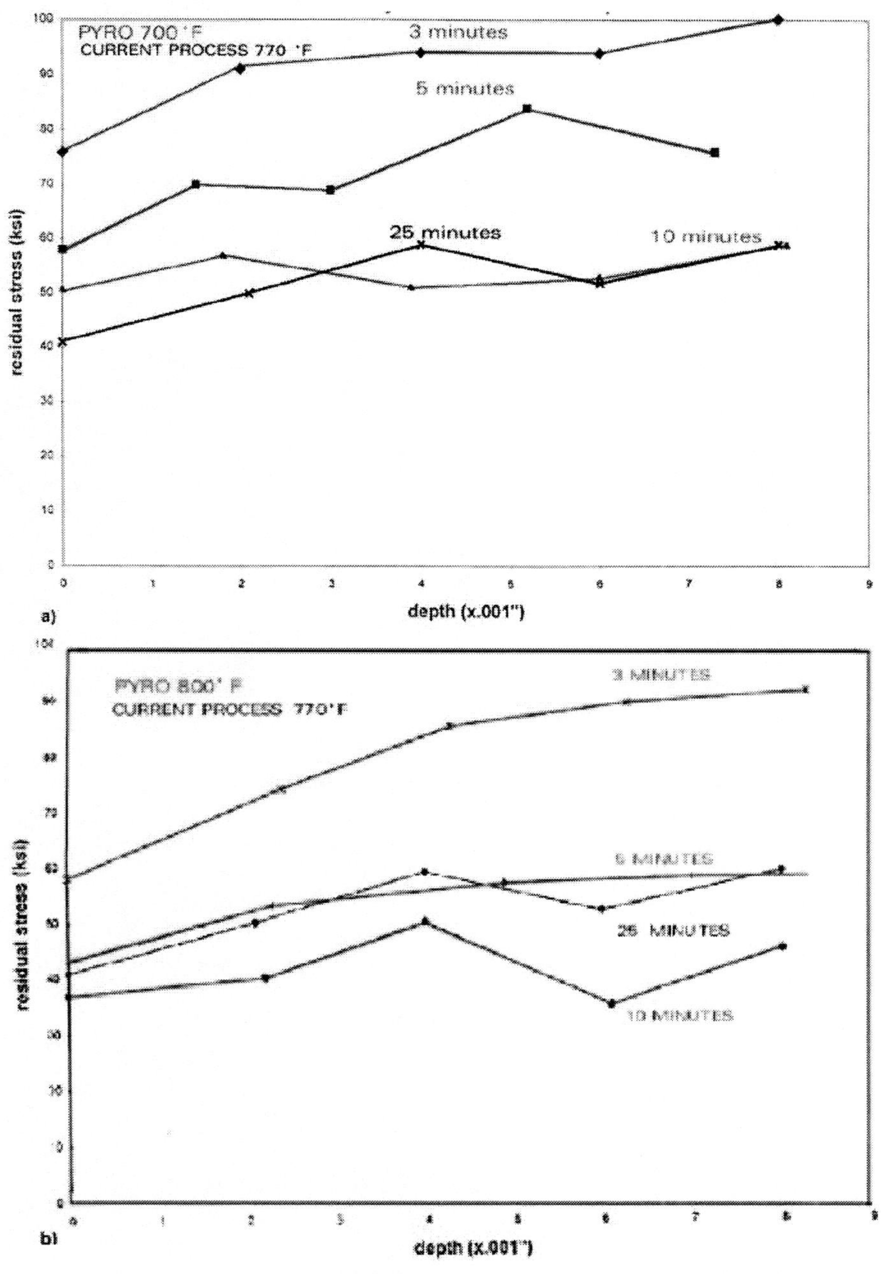

Figure 5 – Residual stress relief: a.) experiment conducted at 800º and b.) experiment conducted at 770°F.

Batch Oven for Continuous Process Simulation

It is typical practice to develop stress-relieving and tempering processes in the laboratory using a conventional batch convection oven. However, it is not unusual to obtain relatively poor correlation between the two ovens. There are a number of reasons for this. One is that it is not sufficient to model the actual process temperature but the heat up and cold down processes are vitally important as well. Recently, a high-speed convection batch oven (Pyro Try-Out Oven) has been developed which exhibits unusual and outstanding temperature tolerance of ±3°C throughout the heating zone. In addition, the actual desired heat-up and cool down process can be programmed as well. Therefore, any in-line stress-relieving process using any oven and any size can be readily simulated using the Pyro Try-Out Oven. An illustration of heating and cooling curves attainable using this oven are illustrated in Figure 6.

Selected Examples of Raid Stress Relieving and Tempering

A comparison of the high-speed stress relieving process (7 min in a Pyro High-Speed Stress-Relief Oven) and conventional stress relief (35 min.) for car engine valve springs has been studied. In both cases, the stress relief temperature was 800°F. The tensile strength for the high-speed process was 275.5 Ksi versus 275.9 Ksi. The as-received wire samples exhibited an average tensile strength of 275.9 Ksi. The average hardness was essentially the same where the average Rc for rapid stress relief was 50.7 vs 50.8 for the conventional process and the average microhardness of the high-speed process was 0.6 Rc higher than the conventional process.

Ten valve springs from each process were fatigue tested for 50 million cycles. At the end of the test, the number of failures for each stress relieving process were equal – two (2) each. Load losses were measured at two heights. Load 1 was measured at 1.880 inches and load 2 was measured at 1.200 inches. The results of these tests are summarized in Table 3. Based on failure and load loss results, it was concluded that the fatigue life of the valve springs produced by both the high-speed stress-relief process was a good or better than those produced by the conventional process. Today, car engine valve springs are now commonly stress relieved using a high-speed stress relieving process (using a Pyro oven).

Table 3
Load Loss Results for Automotive Valve Springs

Stress Relief Process	First Load Height (1.880 in.)	Second Load Height (1.200 in.)
Conventional Batch Oven	3.90%	1.80%
High-Speed Stress Relief Pyro Oven	1.90%	1.70%

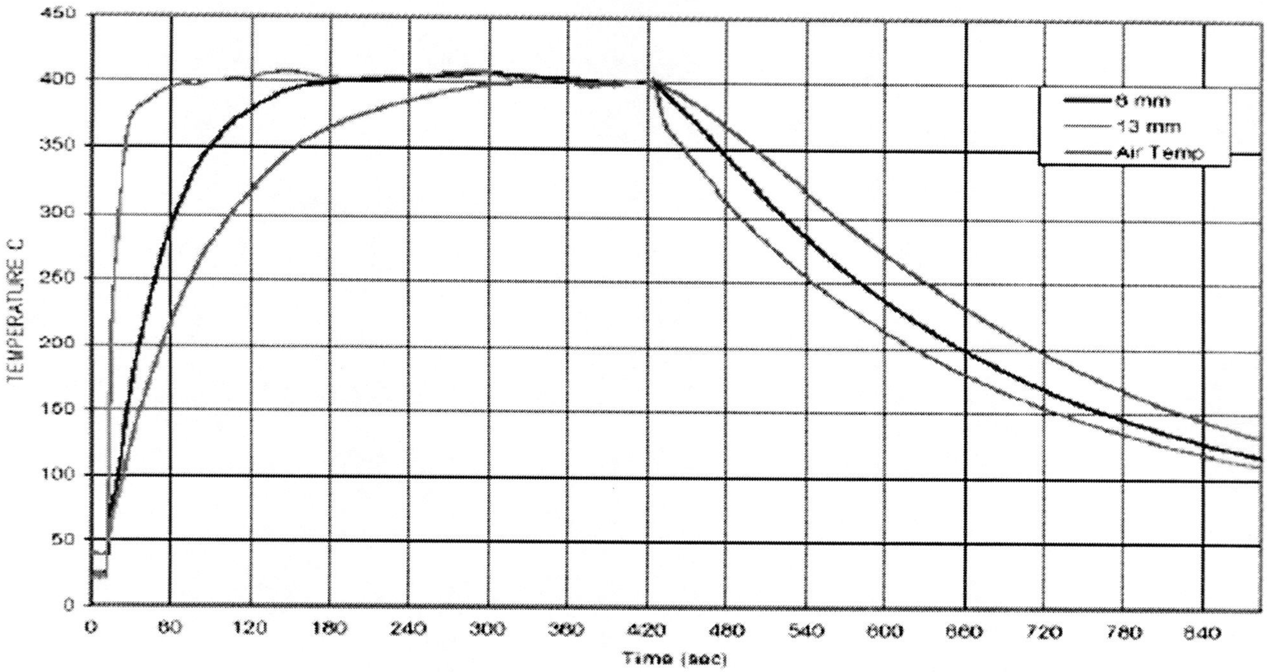

Figure 6 – Illustration of typical heating and cooling curves attainable with a Pyro Try-Out Oven.

X-Ray diffraction measurement comparison was made on automotive tension belt springs. The results shown in Figure 7 illustrate that essentially the same amount of stress relief was achieved by both the conventional and the high-speed process.

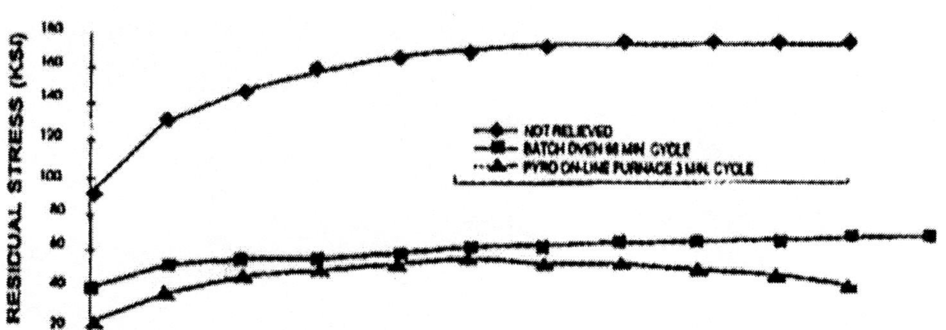

Figure 7 – Comparison of x-ray residual stress measurements on automotive belt tension springs after the conventional and high-speed stress-relief process.

Currently, various high-speed tempering processes have been successfully developed using Pyro ovens. These include automotive axles, hypoid gears and CV joints. Detailed results of these studies will be reported in a subsequent paper.

Conclusions

In this paper, an overview of the metallurgy of stress-relieving and tempering has been provided. This discussion included a brief review of methodologies used at the present time to calculate stress-relief and tempering times. It was shown that although soaking times and temperatures were generally fixed by the steel chemistry, substantial reductions in process times can be achieved by accelerating the heat-up time by designing more efficient heat transfer between the heated atmosphere and the load by using high-speed convective, turbulent flow which also provides for significant improvements in temperature uniformity throughout the load. The use of a heat transfer simulation (Pyrograph) to facilitate the process design process was described. Also described was the development of a new bath try-out oven which successfully models any in-line continuous process. Selected examples illustrating successful high-speed stress relief were also provided. From this discussion, it is clear that substantial process design efficiency and property improvements which utilize less floor space and provide for greater production productivity are possible using a high-speed stress relief or tempering process.

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