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Intricacies of Induction Tempering for Automotive Industry

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Introduction

The tempering process takes place after steel is hardened, but it is just as important in metal heat treatment. A variety of microstructures and mechanical properties of steel can be produced by tempering. This presentation discusses some subtle features of using induction tempering in the automotive industry as well as intricacies of development of modern in-line induction tempering machines.

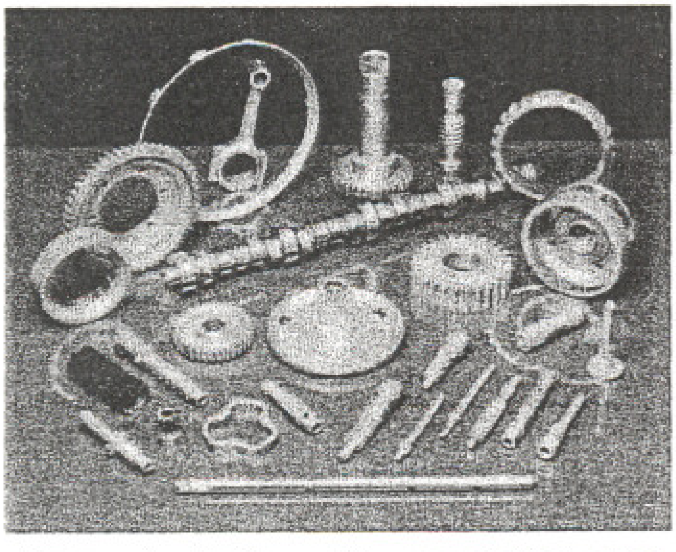

Figure 1. Racks, rods, camshafts, axles, gears, and other critical components are good candidates for induction tempering

The core of this presentation is based on materials published in [1-5].

The main purposes of tempering are to increase the steel's toughness and ductility, to relieve internal stresses, to eliminate brittleness and, in some cases, to improve shape stability and homogenization.

The transformation to martensite through quenching creates a very hard and brittle structure. Untempered martensite is typically too brittle for commercial use and retains a large amount of internal residual stresses. Re-heating the steel for tempering after hardening and quenching leads to a decrease or relaxation of these stresses and develops a tempered martensite microstructure. In other words, by tempering it is possible to improve the mechanical properties of the workpiece and reduce stresses caused by the previous hardening stage without losing too much of the achieved hardness. Tempering temperatures are always below the lower transformation temperature. Parts shown on Figure 1 are good candidates for induction tempering.

A conventional way of tempering is to run the parts through a tempering furnace (gas or infra-red furnace), which is typically located in a separate production area and therefore requires extra space, labor and time for parts transportation. Tempering in the furnace is a time-consuming process that may take up to 2-3 hours. To overcome these disadvantages, short-time induction tempering was developed.

Induction tempering temperatures depend upon the application and are usually in the range of 120-600°C (248-1112°F). If the carbon steel is heated up to less than 100°C (212°F), there is no change in the metal structure, and the effect of tempering will not take place. Low temperature tempering of carbon steels is typically done at temperatures of 120°C-300°C (248°F-572°F). The main purpose of low temperature tempering is stress relieving. Hardness reduction typically does not exceed 1-2 points HRC. If the tempering temperature is higher than 600°C (1112°F), essential changes in the structure of the steel may result that can lead to a significant loss in hardness. Hardness reduction exceeds 12-15 points HRC and maximum hardness is typically in a range of 36-44 HRC (unless it is alloyed steel).

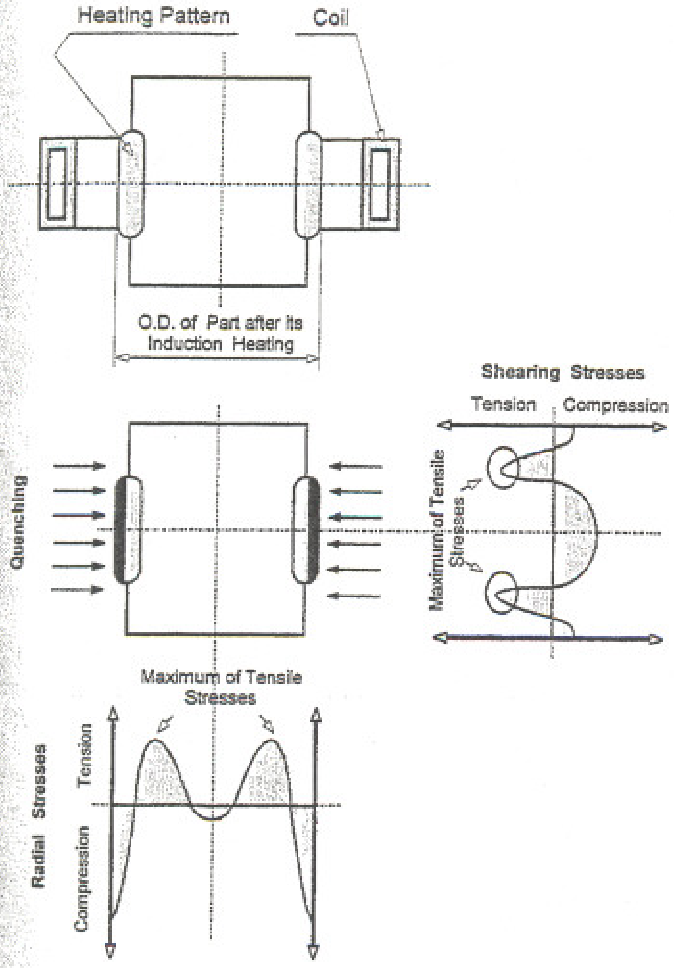

Figure 2. A complex pattern of ***residual*** stresses forms in a carbon steel cylinder after induction heating and quenching

Time and temperature are two of the most critical parameters of induction tempering. In short-time induction tempering, in order to provide the similar effect as in long-time furnace tempering, it is necessary to utilize higher temperatures. There are several ways to determine time-temperature correlation between conventional long-time low temperature furnace tempering and short-time higher temperature induction tempering, including Hollomon-Jaffe equation, Grange-Baughman tempering correlation, etc.

Stress Appearance During Induction Hardening

Tempering is always a reasonable compromise between maintaining the required hardness and obtaining low-stress, tough and ductile microstructure in the metal. Since one of the most important goals of tempering is stress relieving, let us first examine how stresses appear during induction hardening [1-7]. The mechanism of formation of residual stresses here is different than in other heat treatment processes including carburizing and nitriding.

Generally speaking, there are two different types of stresses: thermal stresses and stresses due to phase transformation. Thermal stresses are caused by different magnitudes of temperature and temperature gradients. Phase transformation stresses occur due to microstructural changes taking place as a result of the formation of austenite, bainite or martensite. The total stress is a combination of both components. At different stages of heat treating the impact of both components on total stresses is different.

Figures 2 and 3 illustrate the dynamics of stress appearance (macroscopically speaking) during induction hardening of a carbon steel cylinder [2,6,7]. At the first stage of the heating cycle, the section of cylinder located under the coil will try to expand. The temperature of the workpiece at this point is relatively low (less than 500°C/932°F). During this stage, carbon steels have a non-plastic condition and cannot easily expand. As a result of that, stresses build up within the workpiece. The temperature rise will result in the appearance of increasing compressive stresses at the surface (Figure 3). In the temperature range of 520-750°C (968-1382°F) the steels undergo plastic volumetric expansion and the stresses start to decrease. Finally, when the temperature exceeds 850°C (1562°F) the steel surface freely expands, the diameter of the heated area becomes greater than its initial diameter. Since the yield point of surface layer is considerably lowered at elevated temperature (which is in the state of austenite), the material will flow plastically. As a consequence, stresses at the surface significantly decrease.

After the quenching fluid is sprayed onto the heated surface, the outside layer quickly looses its plasticity and tensile stresses appear at the surface of the workpiece (Figure 3). There is a pronounced maximum of tensile stresses at the surface of the workpiece. This maximum typically occurs just above M_s temperature. Appearance of martensite reduces the surface tensile stresses and leads to the compressive stresses at the surface. Finally, when the entire part is cooled down, a complex combination of compressive and tensile stresses exist within the workpiece body (Figure 2).

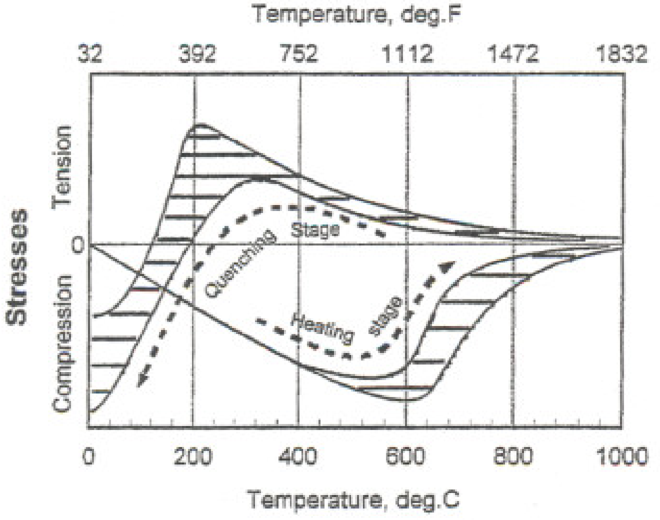

Figure 3. Surface stresses of a carbon steel cylinder during a heating and quenching

The compression stresses in the surface are typically useful. They provide certain protection against crack propagation caused by microscopic scratches. In addition, these residual stresses are very beneficial to the parts which experience bending and torsion applied stresses during their service life.

It is imperative to mention, that just below the hardened case depth there is a maximum of tensile residual stresses located (Figure 2). It is a dangerous area of the part. This maximum is primarily responsible for sub-surface crack initiation.

The overall residual stress condition increases brittleness and notch sensitivity, which reduces part reliability. Therefore, it is necessary to relieve some stresses on the part trying to keep useful compressive stresses at the surface and removing the tensile stresses further away from applied stresses.

Basically, there are two ways to perform tempering by induction: self-tempering (or tempering by residual heat) and induction tempering.

Self-Tempering (Tempering by residual heat)

The principles of self-tempering after induction hardening are illustrated in Figure 4. During the initial stage of induction heating of the steel cylinder, an intensive heating of the surface layers takes place. As shown in Figure 4, after 5 sec. of induction heating the surface layer reached its required final temperature for given steel or iron. The core temperature did not rise significantly because of several factors including the skin effect, the high power density, and the short heating time. Due to these factors, the heat soak from the surface toward its core was not sufficient.

After the heating stage is complete, the quenching begins. In the first stage of quenching the high temperature of the workpiece surface layer begins to lessen. Figure 4 shows that after 2 sec. of spray quenching the surface temperature will be drastically reduced. The maximum temperature of the workpiece will be in the internal layer below the surface. At the same time, because of the thermal conductivity of the steel there will be an increase in the core temperature (the heat soaks from the surface toward the core). After 6 sec. of quenching, the surface temperature will decrease almost to the temperature of the quenchant.

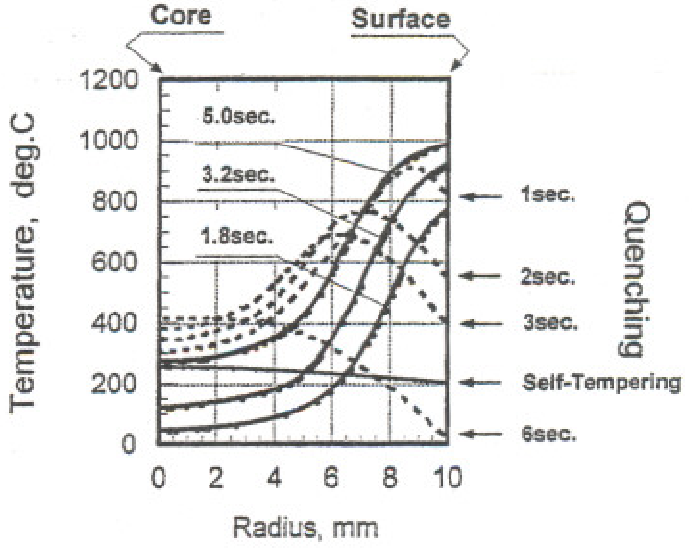

Figure 4. Dynamics of induction heating of a carbon steel cylinder (20mm O.D.) and its cooling during quenching (F=10kHz)

—— Heating
······ Quenching

At the same time, a considerable amount of heat is still retained inside the cylinder (i.e. in Figure 4, core temperature exceeds 400°C/752°F). If at this moment the supply of quenching fluid is cut off, the part will begin to be heated through due to the accumulation of internal heat. After a certain time, the surface temperature will be increased to a value higher than it had been when the quench was cut off. With proper selection of the quenching condition, the heat that is retained inside the part, can be used for carrying out the tempering. Typically, self-tempering temperatures do not exceed 260-290°C (500-554°F) and in the range of 210-240°C (410-464°F).

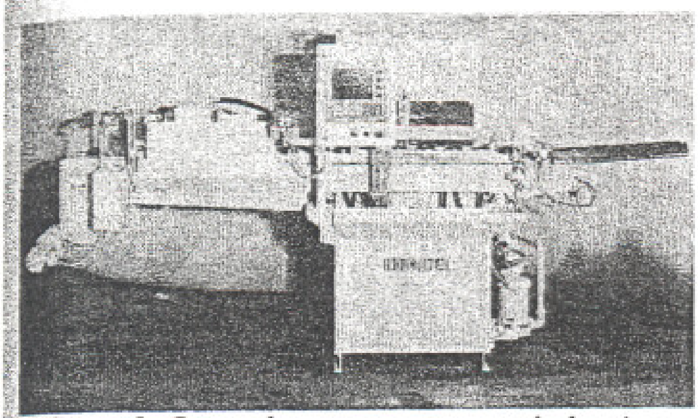
Figure 5. General purpose compact induction tempering machine

To ensure that the self-tempering process is always performed correctly, several precautions must be taken. The energy introduced to the part and the heating time have to be monitored, to ensure a constant amount of residual heat. The quench flow, quench time, and quench temperature should be monitored and held within close tolerances to ensure that the same surface temperature after re-heating is always achieved. Moreover, in many cases an infrared pyrometer is used to monitor the surface tempering temperature.

It is easy to use self-tempering when the part has a large mass and single-shot induction hardening is applied. In the case of a complex shaped body or when scan hardening is applied, it is more difficult to use this type of tempering because the core temperatures are different over the scanning length. The amount of heat stored as well as the heat sink underneath each section of the hardened case must be the same; otherwise, the temperatures achieved after heat soaking will be different and the tempering result will be unacceptable.

Sometimes a "quench-soak-quench-soak" cycle is used. This includes the heating stage, first quenching stage, first self-tempering, second quenching stage, and final self-tempering. Such a method allows one to obtain unique properties of the workpiece.

Induction Tempering and Its Features

For those parts that cannot be self-tempered, the induction tempering method can be applied. Typically, it is not recommended to use the same inductor for hardening and tempering. There are several reasons for this.

First reason has to do with the fact that in induction hardening, in order to obtain the required hardness pattern of the complex shaped workpiece, it is necessary to re-distribute electromagnetic field and introduce more energy within certain areas.

Second, the power densities during hardening are much higher than with tempering. Therefore, with tempering it is necessary to heat the surface at a much slower rate to achieve a low temperature gradient from the surface to case depth. Otherwise the surface could exceed the required tempering temperature, which would result in an unacceptable soft surface.

Third, it is often preferable to use a lower frequency for tempering because the tempering temperatures are always below the Curie point. As a result, the heated part retains its magnetic properties and the skin effect is very pronounced. When a single frequency is used, the penetration depth in the case of induction tempering is much smaller compared to its value even during the magnetic stage of induction hardening. This holds true due to the higher value of magnetic permeability of steel during induction tempering compared to its value during induction hardening [1]. Therefore, in induction

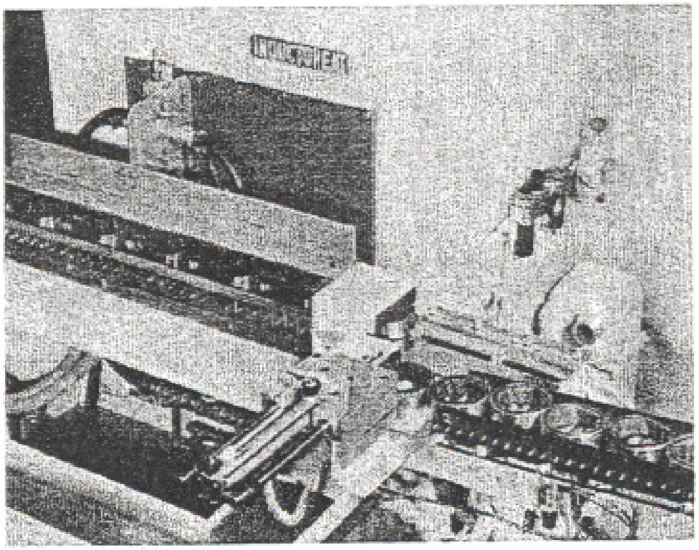
Figure 6. Closer look at unitized in-line induction tempering system

tempering, in order to increase the current penetration depth in the part, it is more effective to use a lower frequency. Sometimes, an induction coil designed for a high frequency might have a poor performance for low frequency applications and visa versa.

In addition, it is highly recommended that the temper inductor should not heat just the selected hardened area but the much larger region or even an entire workpiece. A loosely coupled multi-turn coil can be used for this purpose.

There is a common misconception that tempering removes all internal residual stresses. It does not. However, tempering significantly decreases stresses. In addition, it shifts a maximum of dangerous tension residual stresses, which is typically located just below the hardened area (Figure 2) further away from the surface and applied stresses.

Tempering makes the irons and steels more ductile and reduces the possibility of cracking. However, it is important that the time from quench to temper be held to a minimum. If this “transient time” is long enough, the internal stresses may have enough time to allow shape distortion or cracking to take place. Therefore, a long transient time between quenching and tempering will decrease or even eliminate the tempering benefits.

Since tempering is a diffusion-type phenomenon, the time for tempering is much longer than that required for hardening and quenching. It may take seconds to induction harden but tens of seconds or even minutes to induction temper.

In the case of induction tempering of complex shaped parts (i.e. gears or other critical components), the choice of frequency, power density and coil geometry is dictated by a need to apply enough energy into certain areas of the body. For example, in gear tempering applications, it is necessary to induce enough energy into the root area of the tooth without overheating its tip.

The root of the gear is the most critical area because the maximum concentration of residual stress and applied stress are located there. As a result, cracks and distortion occur primarily in the root area. Therefore, this area needs to be stress relieved in the first order. However, there are three factors which make this task quite complicated. First of all, the root area does not typically have a good coupling with the induction coil compared to the gear tip. Because of that, it is more difficult to induce energy there. Secondly, the tempering temperatures are below the Curie point, therefore the gear is magnetic and the skin effect is pronounced. This results in a power surplus in the tip of the tooth compared to its root. The third factor deals with the fact that there is a significant heat sink located under the gear root (under the base circle). In order to overcome the above mentioned difficulties, induction heat treatment manufactures have created several new design concepts which have resulted in the development of advanced induction gear tempering machines.

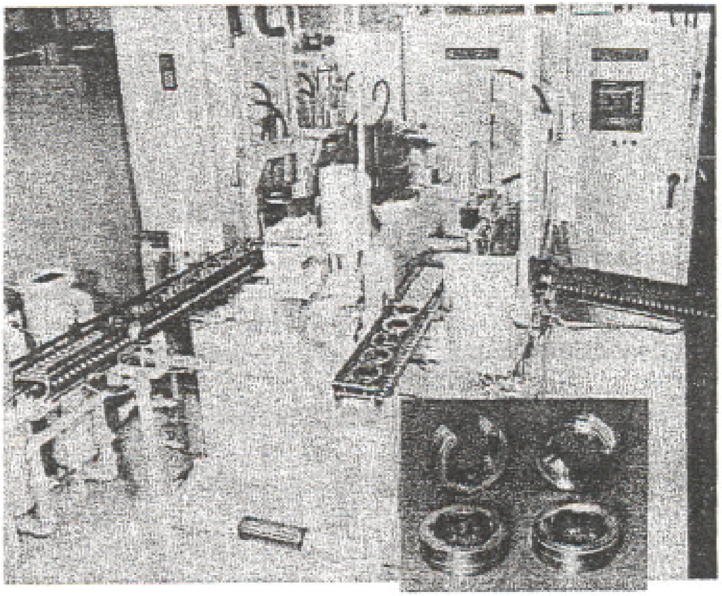

Figure 7. Inductoheat's unitized induction heat treating machine for hardening and tempering of crossgrove disks

If a workpiece has been hardened on the inside surface then the tempering coil should be located around the part, so the temperature can slowly increase from the outside surface toward the hardened layer on the inside surface. Proper energy control is a very effective method to carry out the tempering without the danger of overheating the hardened surface.

A similar coil design idea can be applied for a hollow workpiece that has been hardened on the outside surface. In this case, it is very effective to locate the tempering coil inside the hollow workpiece.

In cases, when there is the wide variation of mass distribution, it will not be wise to design an inductor that heats only the hardened case as the induction hardening inductor does. Due to a different heat sink effect, the inductor should also induce the heat into areas that are not heat treated such as the flange. These areas will then act as a heat buffer and may be at a temperature slightly above the tempering temperature. This will allow for inconvenient areas to also be heated.

Since a maximum of dangerous tension residual stresses is typically located below the hardened area, somewhere within the transition zone (Figure 2), it is necessary to expand the heated area not only to the case depth (hardened depth) but further into the transition zone as well.

With these types of inductors it is possible to temper workpieces with complicated shapes and mass distributions such as, for example, CV joints, which are hardened inside the bell and on the outside of the shaft.

Since the tempering inductor is typically loosely coupled to the workpiece, this allows the tempering coils the ability to lightly heat even the edges, grooves, and other critical regions. Often a "heat-soak" cycle is used. This allows the heat to soak all the way through the workpiece without overheating the surface.

As a rule of thumb, the heating time for tempering is at least twice the hardening cycle time (heating and quenching). This means that an induction heat treatment machine can have one station for hardening (heat and quench) and two stations for tempering. In this case, the indexing time between the two tempering stations acts as soak time.

A cooling cycle may follow completion of the tempering cycle. A cooling station may be located just after tempering. Another practice is to have a cooling station separate from the tempering machine. In this case, the cooling station is located on an exit conveyor. T reduces the number of stations involved in t machine design.

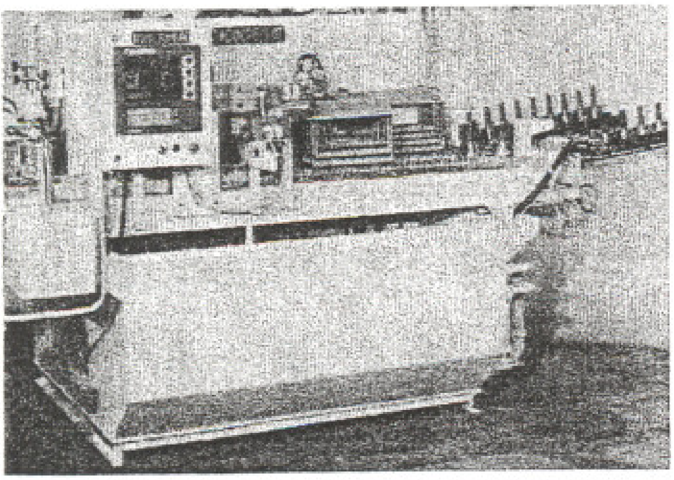

Figure 8. In-line induction temper of constant velocity joints (CV joints). Efficient, compact, clean and quite

The correct process parameters for inducti tempering might be found by hardn measurements and by microscopic evaluation the part's microstructure.

Commercial Aspects of Induction Tempering

The decision to induction temper should carefully considered. Some metallurgists are r comfortable with tempering for short times. Th feel that an oven that heats the entire part a holds it at temperature for hours and not secon or minutes is more reliable. The key to any pa production process is in how the finished produ performs. Induction tempered parts, as any oth machine components, should be thorough tested and evaluated for reliability.

Fatigue and failure testing for inducti tempering should be compared to that in furna tempering of individual workpieces. It important to remember that the surface temperi temperature alone is not a valid indication of proper temper.

If tempering has been done correctly, the will be only a slight loss in hardness. At t same time, the benefits obtained by temperi (including internal stress relief, creation of t required ductility or toughness, shifting of t dangerous maximum of tensile stresses furth away from applied stresses, improvement in t machinability of the steel, etc.) will offset t slight reduction in hardness.

As an example, Figures 5, 6, 7, 8 and 9 sho a new generation of compact in-line inducti tempering machines. Such systems are a dire replacement for furnaces in many application These compact machines require less than ha the furnace floor space. Sophisticated desig allows simplified operating conditions, increas reliability and decrease maintenanc requirements. Many of the parts tempered i these machines have multiple hardened area with both inside and outside surfaces cas hardened. Production rates of the machine show on Figures 8 and 9 are from 60 to 150 pieces pe hour. Whole families of similar parts are ru using a single coil design.

As quenched hardness is in the 60-63 HR range, the tempering process uniformly heats th entire part to a temperature of 190°C to 232° (375°F to 450°F). The total maximum variatio in part temperature is approximately 19° (30°F). The final part hardness is 58-62HRC

Due to an advanced coil design concept the coil electrical efficiency is in the range of 72% to 89%. Life of these coils is often exceeds 800,000 parts.

If induction tempering has been done in a proper way, the advantages of in-line induction tempering, including single part processing, savings in investment cost, environmental friendliness, system compactness, maintenance and labor savings, high energy efficiency, minimum start-up and shut-down time, precise control and monitoring of an individual part in many cases far outweigh the disadvantages and fear of the untried..

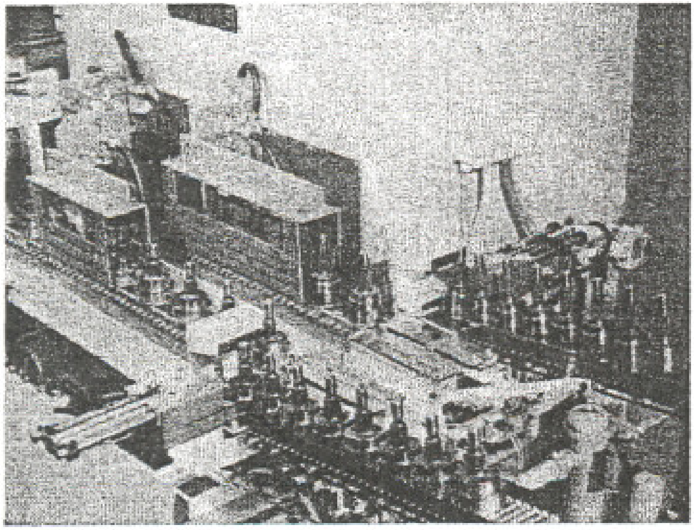

Figure 9. Closer look at Inductoheat's general purpose in-line induction tempering machine which conserves fossil fuels and valuable floor space. Parts are processed in minutes compared to hours as with conventional temper furnaces.

Conclusion

Due to the limitation of space, it was only possible to describe a portion of the features of tempering by induction. The variety of induction heat treatment applications necessitates the use of many different combinations of power supplies, coil design, load matching, process control, and process monitoring equipment. The operational characteristics of the power supply must properly match the coil requirements to obtain the desired results.

There are some other unique factors which make a pronounced effect on the tempering operation. If you have any questions or would like to acquire more information about a subject, we welcome you to contact us at Inductoheat, Inc. Tel. (248) 585-9393; FAX: (248) 589-1062; e-mail: murray@inductoheat.com Address: Inductoheat Inc., 32251 N.Avis Dr., Madison Heights, MI 48071, USA or in Mexico Tel.+52-4-2122215 & 2242835, FAX: +52-4-2141139, e-mail: incotec@albec.net.mx

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