Technical Report 2/2009

Induction heating of steel bars for hot coiled spring production

2009-07-07

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Abstract
The main purposes introducing induction heating of the bars was to reduce the carbon oxide air pollution and to improve the product quality assurance. The gas heated bar furnace was replaced with an induction heating system for the bars. The result was that the local carbon oxides air pollution from the bar heating in the factory was reduced to zero. The risk for quality deviation was reduced with the installed induction heating technique and at the same time the heating capacity was more than doubled. The induction heating and the influence on the spring steel material and the products are described in this report.

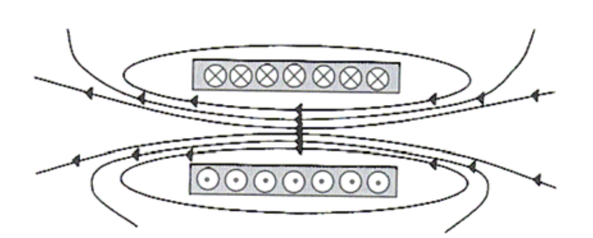
Introduction

When hot coiling springs, the steel bars need to be heated to austenitic temperature before coiling. At this temperature the steel bars are soft and plastic and can easily be formed to specified shape. The hot coiled springs are also quenched in oil from the same heat to receive the high strength needed. The heating parameters for the bars then have an influence on the material and hence also on the performance of the springs. Heating steel to these high temperatures, over 850 degrees Celsius, also consume a lot of energy and therefore is the efficiency of the heating of great importance. For a time Lesjöfors investigated possible technologies for an environment and technical improvement of the bar heating. In the analysis we found that induction technology will give the best conditions to meet the specified targets. The purpose with this report is to present the new bar heating and some results of this investment.


Part of the induction heating line under assembling.

Induction theory

Michael Faraday discovered electromagnetic induction in 1831, at the same time also independently discovered by Joseph Henry. A conductor (wire) with an electric current passing through it, generates a magnetic field around it and the strength of the magnetic field is proportional to the amount of current. The magnetic field can be concentrated if the conductor (wire) wound into a coil with many turns side by side. The magnetic field of all the turns then passes through the center of the coil. A coil formed to the shape of a straight helical coil (similar to a corkscrew) can produce strong magnetic fields. If a "core" of ferromagnetic material, such as a spring steel bar, is placed inside the helical coil, the ferromagnetic core magnifies the magnetic field many times the strength of the field of the coil alone, due to the high magnetic permeability (μ) of this ferromagnetic material (iron).


Electric conductor with magnetic field

From Faraday's law of induction, the changing magnetic field (AC) induces circulating electric currents inside a conductor (wire or bar), called eddy currents. Eddy currents are closed loops of current that flow in planes perpendicular to the magnetic field. The energy in these currents is dissipated as heat in the electrical resistance of the conductor, wire or bar. In this case the eddy currents in the bar are generated by the magnetic field from the conductor (copper coils). The steel bar is the core in the conductor and since the bar mostly contains iron (about 97%) it has high conductivity, and most of the magnetic field is concentrated there. The energy dissipated is proportional to the area enclosed by the loop.

Induction steel bar heating

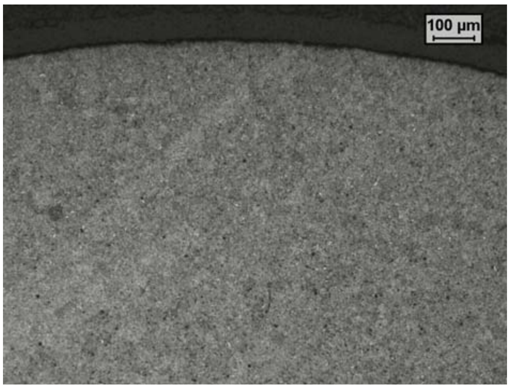
The eddy currents generated by the magnetic field within the steel and the electric resistance in the steel, leads to the heating of the bar. Some heat is generated by magnetic hysteresis losses in the steel up to the Curie point. If the bar is moved through the conductor the whole bar length is heated. The induction heater for the steel bars consists of several conductors (electromagnet coils), through which a high-frequency alternating current (AC) is passed. The conductor coils for steel bars are made of copper. The frequency of the AC power used, is controlled to get optimized energy efficiency and equal distributed heating through the cross section of the bars. The heating goes very fast and the temperature is controlled by the speed of the bar and the currency. The temperature is supervised with optical pyrometers and the speed is controlled with encoders connected to the process computer system. The system have full automatic bar handling, the bars are loaded in bundles and the system deliver single hot bars with correct temperature and speed to the coiling machine. The main components are the high frequency power system, the conductors, the cooling system, the bar transport and handling system and the computer system. The heating capacity is more than doubled compared to previous conventional gas heated bar furnace.

Conductor coils.

Influence on the spring steel material

Spring steel grades for hot coiled springs are designed for quenching and tempering to a condition called tempered martensite, suitable for coil springs. This condition has a high ultimate and yield strength, combined with good fracture toughness all of great value for the load, fatigue and relaxation performance. The heating conditions have an effect on the decarburisation, grain boundary oxidation and of course also on the condition/structure after quenching and tempering. These factors have an influence on the material performance.

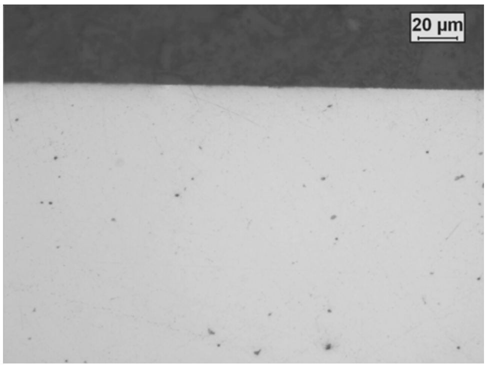
At austenite temperature the carbon in the steel and the oxygen in the atmosphere in contact with the surface, react with each other which lead to decarburisation at the steel surface. The speed of the reaction depends on the temperature and the composition of the atmosphere around the steel surface, hence the time at the high temperature is important. In a normal gas or oil heated furnace it is difficult to control the furnace atmosphere, certain compositions of the hydrogen and carbon monoxide can lead to high decarburisation speed. Also the time the surface is at high temperature is much longer in conventional furnaces.



Metallographic microscope picture, tempered martensite structure (cross section) no visual sign of decarburisation.

If the carbon content in the steel surface is reduced by decarburisation the strength of the steel in the surface is reduced, hence also the fatigue strength and relaxation performance. With induction heating, the time at austenite temperature is extremely short which prevent decarburisation. Also the atmosphere is fully controlled, since normal air is present and the hydrogen and carbon monoxide reaction with the carbon can not take place. Both these advantages lead to a minimum of decarburisation.

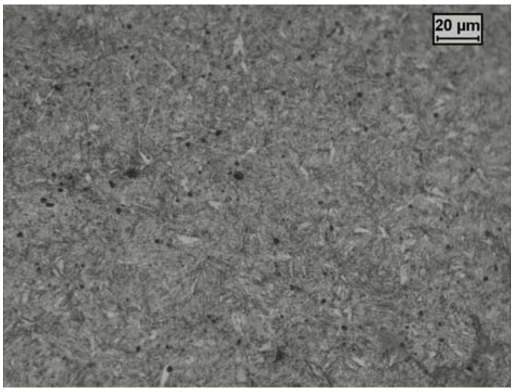
The oxygen and/or carbon monoxide in a furnace atmosphere also lead to oxidation of the iron at the steel surface. Normally this gives an oxide scale on the surface, but at too long time at too high temperature the oxides can penetrate in to the grain boundaries at the surface which reduces the fatigue strength. With induction heating is the time at austenite temperature extremely short compared to normal furnaces. The temperature is also quickly and easily controlled to correct level with power and speed. With the automatic temperature control and supervision by optical pyrometers, too high temperatures are prevented.



Microscope picture from polished cross section, no grain boundary oxidation.

To receive a good martensitic structure, the alloying elements must give their effect on the harden ability of the steel when quenching. This means that the alloying elements must have dissolved in to the austenitic structure before the quenching. This is normally not a problem, except for chromium which in these grades partly forms chromium carbides at lower temperatures. During heating to and at austenite temperature, it takes some time for the carbides to dissolve into austenite. With increased austenite temperature the speed of this process increases. This risk has been carefully investigated and special actions have been taken in the design of the induction line and in the setting of the process parameters. The validation process has shown that the process deliver a normal tempered martensite structure and hardness after quenching. In the presetting operation is also the material strength automatically evaluated for each batch.


Hot bar under coiling before quenching.



Microscope picture, tempered martensite structure after quenching and tempering.

When steel is heated from room temperature to austenite temperature, the grains re-crystallize to the smallest possible grain size controlled by the chemical composition of the steel. After the grains have re-crystallised they start to grow in size. The speed of the growth increases with increased temperature, hence the time at the austenite temperature control the grain size together with the chemical composition. Steel with small grain size have higher fracture toughness compared to steel with larger grains hence higher fatigue resistance. The grain size is normally inspected by using the ASTM standard method. The ASTM scale have grade values from 0 up to over 10 where 6 is an average grain diameter of 44 microns and 8 is average diameter 22 microns (0,022 mm). With induction heating is the time at austenite temperature extremely short, compared to normal furnace heating. Actually induction heating gives the best potential to receive a fine grain martenistic structure of all heating technologies known at present. The induction heating system installed gives grain size ASTM 8 or better.

Environmental effect

There are a number of important advantages with induction heating. There is no heating up time of the system as for conventional furnaces. Heating up the refractory in normal furnaces can take many hours before any production can start. The energy efficiency with induction is high, mainly because the energy is generated in the steel directly and there are no exhaust gas energy losses. One other factor is that during a stop in the production, the power for the heating is zero while a conventional furnace must be held at correct temperature during the stop. All this lead to a high efficiency of the energy used. Less energy consumption means less environmental impact.

For induction heating is electric power needed and in this case is the power generated by water, wind or other electric power technologies. In the Nordic countries almost all electric power production is made with technologies without any carbon oxide air pollution. The previous furnace for the bar heating used about 100 ton butane gas per year. Butane gas (C_4H_{10}) is a hydrocarbon, which in the burning reaction give carbon oxides and water (steam) in the exhaust outlet.
The investment in induction heating for the bars, is a big step to an air pollution free hot coil spring production system. The energy consumption for the bar heating is reduced with more than 50 % and the reduction of carbon dioxide is as average about 275 tons of fossil CO_2 per year, calculated with the formula (thermal value) x (consumption) x (CO_2 emission value for fossil LPG).

The normal furnace did not give any contribution of fuel NO (nitrogen oxide) as coal does and the prompt NO_x was considered as negligible. But thermal NO_x formation, which is highly temperature dependent, took place when combusting the butane gas with air at the high temperatures needed for heating the steel. The reduction of NO_x emissions are not easy calculated but a rough estimation is that the reduction in weight is about 1/10th of the CO_2 air pollution.

Effect on the spring products

As described above, the investment in induction bar heating have improved the quality assurance regarding decarburisation, oxidation and grain size. The new heating system has in other words lowered the risk for negative effects from these material parameters. By a minimum or decarburisation free surface of the bars, the fatigue and relaxation is optimised and only dependent of the steel and design stresses in the spring. The residual stressed introduced by the shot peening will also be secured on an equal and high level. The minimized oxidation at the steel surface leads to very good surface smoothness and no risk for grain boundary problems. This gives a high security against breakages caused by these types of defects. The small size and low spread of the grain size lead to best possible fracture toughness at specified strengths, which assure best fatigue performances. A high toughness reduces the risk for fatigue initiations by small non metallic inclusions and surface defects. With the new induction heating the quality assurance of several important spring quality factors have been improved.

Discussion

Literature studies, study of induction heating systems in operation and laboratory tests was carried out before the investment decision was made. The project also contained full scale investigations at the manufacturer and exhaustive controls after installation and when the validation process was fulfilled. The number of tests and investigations has shown with high probability that the induction heating system heats the bars according to given specifications.

Laboratory induction tests.

Acknowledgements
Doctor Giovanni Calvi, Induction s.r.l. Italy
M.Sc. Lennart Sibeck, Bodycote CMK, Bofors Sweden
M.Sc. Sofia Brorson, Bodycote CMK, Bofors, Sweden
M.Se Juha Perttula, Imatra Steel, Finland
Technical manager Jan Beijbom, Rukki Sweden AB, Virsbo Sweden
Managing Director Dan Manninen, OY Lesjöfors AB
Production Manager Kennth Lindholm Oy Lesjöfors AB

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Carbide dissolve and grain size, Kari Blomster, Fermater OY Finland
Naturvårdsverket Sweden, Calculation of fossil discharge