State-of-the-art induction technology for crankshaft hardening plants

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Crankshafts are used in combustion engines, transforming the con rod's stroke into a rotatory motion for driving the axle shaft. Along with this, torsional and flexural fatigue appears and demands a special heat treatment process. The induction hardening with a rotating crankshaft has mostly replaced competitive methods and provides the engine builders with a flexible production process for varying geometries, different hardening zones as well as increasing production rates.

The growing middle classes in societies around the world result in increased mobility over the long term. While car sales have reached a peak in Western nations, there is still no end in sight in Asian countries in particular. Growth rates in the mid double-digit range are fairly common and are leading to a similar increase in the production of combustion engines. As well as conventional car engines, however, more and more engines for rail-bound vehicles and marine engines are being produced to meet the high demand on land and sea. In terms of marine engines with large crank-shafts in particular, a clear trend toward more eco-friendly gas engines, where the crankshafts are subject to higher loads, is emerging as a result of rising marine fuel costs and the reduction in allowable emissions. Another growing field of application is various-sized diesel generators for the local generation of electricity.

Induction-hardened crankshafts are primarily used here, and their lengths – depending on the application – range from 500 mm to over 10 m. The greatest significance here is attached to induction hardening with a rotating crankshaft as well as locally hardened bearings. The reasons for this are the benefits it offers compared to other techniques, resulting in a high level of reproducible hardening results. Even slim-design bearings, if induction-hardened, can withstand high loads, meaning smaller motors can be used.

THE INDUCTION SURFACE HARDENING PROCESS

Induction hardening can be divided into two consecutive process stages: 1) induction heating, and 2) quenching with a cooling medium. Both sub-processes are equally important in attaining reproducible process results.

With induction heating, an alternating current is passed through a coil, i.e. the inductor - the shape and size of which is adjusted to the workpiece. This current generates an alternating magnetic alternating field, which in turn induces eddy currents in the material (**Fig. 1**). The induction penetration depth depends on the frequency of the alternating voltage. The higher the frequency, the lower the penetration depth (skin effect). Therefore the temperature and depth of heating can be influenced by the frequency, the current strength in the inductor, and the duration of the current supply. Unlike other heating techniques, induction generates the heat in the material itself. Therefore the distribution of heating power is not only depending on conduction. The advantage of this is that with

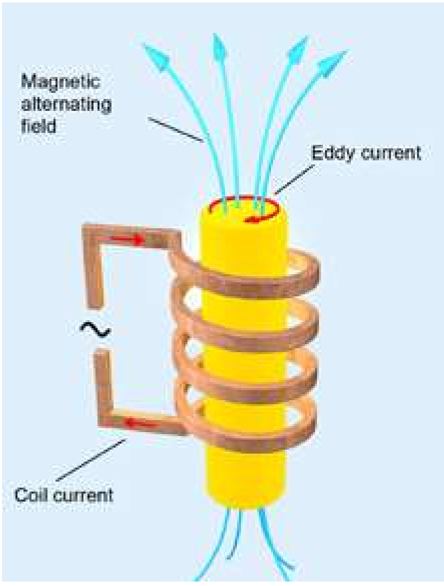

Fig. 1: The induction principle

Fig. 2: Half-shell inductor for induction surface hardening of crankshafts

induction heating, overheating of the surface is considerably lower with the same level of power transmitted into the material. As a result, extremely high power densities can be used. To prevent the workpiece from being heated fully through by heat conduction, the duration of the current supply is kept short. Consequently, process cycles of just a few seconds are possible – depending on the relevant process – with small heat penetration depths.

According to the induction principle, the material is heated to a temperature above the material-dependent A3-temperature. Here the α iron (ferrite) which exists at room temperature is converted into γ-iron (austenite), in which far more carbon can be released from the existing carbides than in ferrite. For this reason, the steel must contain at least 0.2 % carbon in order to be hardened. Otherwise carburization would have to be carried out accordingly in an upstream process to add the necessary carbon.

The quenching process which follows involves the rapid, controlled cooling of the austenitized material. The fast cooling exceeds the diffusion velocity, precluding a regression to the original ferritic-pearlitic structure. Due to the additional carbon atoms, the microstructure is no longer able to convert into body-centered cubic α-iron. Instead, body-centered cubic martensite, tetragonally distorted by the carbon atom, is created. At the same time the cooling rate, which can be controlled using various quenching media (water with additives), influences the extent of martensite formation. As a rule, faster cooling results in more martensite formation.

In its quenched state, the material is very hard and brittle. Subsequent tempering may be used to reduce the hardness and attain the desired properties for material use (hardness, tensile strength and ductility).

ADVANTAGES OF ROTATIONAL INDUCTION SURFACE HARDENING

Rotational induction hardening has developed into the global standard for engine manufacturers. While it has been used and further developed in Europe for decades now, engine producers in Asia – China most of all – have adopted this technique from their Western joint venture partners and integrated it into many new works. The increasing minimization of engine components worldwide due to rising fuel prices and pressure to reduce CO_2 emissions, is currently leading to a shift in the NAFTA countries. Whereas in the past NAFTA nations primarily used non-hardened crankshafts – which were nevertheless large in size – for large displacement motors, they are now increasingly using rotationally induction-hardened crankshafts with much smaller dimensions. The emerging supercharged 3- or 4-cylinder engines are every bit as good in terms of their performance as their larger predecessors.

This development stems from the clear benefits offered by the rotational induction hardening process, with which the crankshaft is clamped between the chuck and tip, a rotary motion is induced, the crankshaft is heated using half-shell inductors and then quenched with an integrated spray head.

With rotational hardening, the car crankshaft is rotated at 30-60 rpm under a half-shell inductor (**Fig. 2**). Therefore the entire circumference of the bearing is brought to austenitizing temperature at the same reproducible depth - an essential pre-condition for the creation of an evenly formed hardening zone.

An angle at circumference of almost 360 ° (of which 180 ° is with forced quenching by spray head) is then available for the equally critical quenching process, thereby ensuring the critical cooling rate for producing a homogeneous, martensitic structure is actually achieved.

A geometric feature of a crankshaft is the various mass ratios around the circumference of the bearings, especially the pin bearings. Whereas there is scarcely any material at top dead center at the sides, the cheeks of the pin bearing are located at bottom dead center of the same bearing on both sides. Since with induction hardening, as described, the heat is generated in the component itself, the mass distribution in the vicinity of the heating zone results in a distinctive heat flow which necessarily produces various temperatures. To prevent this, rotational hardening allows for what is known as "power pulsing". Here the optimum amount of energy can always be supplied as a function of the crankshaft angle of rotation, ensuring consistent conditions for heating are produced at all times. According-ly, less energy is supplied at the top dead center of the pin bearing, since less energy is able to dissipate into the surrounding areas; at bottom dead center, however, more energy is supplied to level out the heat flux into the cheeks.

The above-described rotational machining process, which can be precisely controlled, not only guarantees a reproducible hardening result, it also minimizes the distortion of the crankshaft. This results from the local material growth in the heating zone, especially during hardening of the radii. Distortion is minimized by a combination of warp simulations, intelligent hardening sequences for the bearings, selective power pulsing and specific mechanical workpiece guides. The result is low-distortion crank-shafts with precisely hardened surfaces and the desired microstructural properties [1].

In summary, it can be concluded that with rotational induction hardening, both critical sub-processes "heating above the austenitizing temperature" and "quenching at the required cooling rate" for the purpose of reproducible martensite formation, can be very well controlled.

While conventional process monitoring of the temperature, composition, cleanliness and flow of quenchant is used for the quenching process, SMS Elotherm has developed a technique for the heating process which reliably calculates the process energy required for austenitization of the workpiece.

This is where the patented workpiece effective power measurement system [2] is used. This system monitors exactly what electric power is actually induced in the workpiece and consequently converted to thermal energy. The main feature of this system is that it takes into account the entire power loss between the energy supply and inductor, with the result that the active energy is not only shown as a parameter for the quality of the heating process, it is also recorded. Compared to other systems, which only measure the converter output power, the workpiece-based recording of the active power enables a full check without the otherwise essential quality inspection where the workpiece is destroyed. For critical parts like crankshafts in particular, this offers engine builders a system which meets both the high demands of modern quality audits and satisfies the conditions for full parts tracking.

ROTATIONAL HARDENING VS. NON-ROTATIONAL STATIC HARDENING: A PROCESS COMPARISON

Rotational hardening is the established global standard method of hardening crankshafts.

Parallel to non-rotational static hardening a process has been developed whereby the bearings of the crankshaft are heated by inductors which almost fully surround them.

While on the one hand this method is impressive due to the simpler machine construction involved – as the component does not need to be rotated – there are process-related restrictions in terms of achieving a homogeneous, martensitic structure on the other hand.

Depending on the process, uniform heating is only possible to a limited extent, as the specific inductor design is not perfectly suited to even heating, i.e. it does not help achieve homogenization of the heating zone due to the lack of rotation.

Furthermore, the inductor hinders free access of the quenching medium to the bearing, resulting in uncontrolled cooling which may impede the formation of martensite. Both sub-processes, i.e. austenitization and quenching, can be perfectly coordinated during rotational hardening to create a reproducible, homogeneous hardening zone.

While only one power can be used for heating with non-rotational static hardening, thereby resulting in the need for a compromise solution to ensure the material does not overheat at top dead center and does not become sufficiently warm at bottom dead center, angle-dependent power pulsing during rotational hardening allows for the best level of energy input in each case.

A direct comparison of both techniques also shows that rotational hardening is far less likely to result in local overheating in the area of the oil holes and brings about a more consistent structural transformation over the bearing cross-section.

The described options for reducing warpage of the crankshafts during rotational hardening, such as power pulsing, specific workpiece supports or suitable hardening sequences are not provided per se by static hardening. Consequently, greater warpage can be expected with non-rotational hardening, resulting in acentric positioning in the inductor and ultimately in increased tool wear.

In summary, the process-related advantages of rotational hardening are overriding, thereby justifying a more complex machine construction, with the result that this method has been adopted by almost all engine builders worldwide.

Fig. 3: EloCrank™ for automotive crankshafts (source: SMS Elotherm)

Fig. 4: EloCrank™ XL for large crankshafts (source: SMS Elotherm)

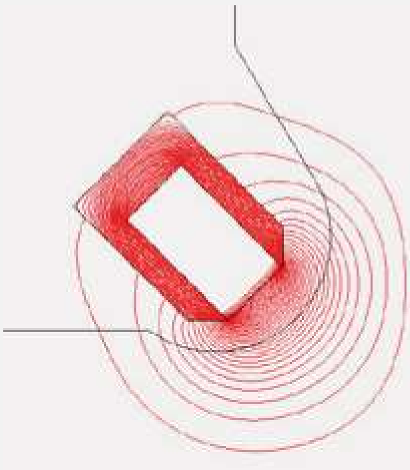

Fig. 5: Example of magnetic field propagation in the undercut

FROM ELOCRANK™ TO ELOCRANK™ XL

The various applications of crankshafts, from small motors for garden equipment to automobile and HGV engines, and from diesel engines to generators and marine diesels have led to the development of a correspondingly wide variety of sizes and geometries. Accordingly, there are various crankshaft hardening machines available which, thanks to their modular design, each cover a wide geometrical range.

EloCrank™ from SMS Elotherm is a typical example of a flexible induction hardening machine for automotive crankshafts of varying sizes. Offering flexibility in terms of the length and enveloping circle of the crankshaft, both the number of machining stations and the quantity of individual inductors can be chosen as a function of the number of units produced.

The modular structure and machine tool design – with process view and user-friendly menu options – are complemented by the loading capabilities that are adapted to suit the engine builder's production flow. As well as the conventional walking beam transfer system, shuttle transfer solutions and direct machine loading through a gantry are also available.

Therefore with the ability for automatic change-over to various workpieces, one machine with two hardening stations (**Fig. 3**) can harden 4-cylinder crankshafts within a cycle time of around 30 seconds, for example. Various tempering processes for reducing the residual stresses, such as induction tempering or tempering from the residual heat are also possible.

EloCrank™ L is the system used for crankshafts in HGVs. The main difference here - in addition to its ability to harden crankshafts of up to 1,500 mm - is the linear traversing carriage with the inductors. It offers businesses great flexibility in reacting to different unit volume requirements, as it can be operated with a minimum of inductors for the successive hardening process or with a full tool complement of 13 transformer-inductor units.

A modular system of induction hardening machines from the EloCrank™ XL series is available for large crankshafts. Above all, its machine beds of varying lengths enable the successive hardening of crankshafts with a length of up to 12 m long and a weight of 8 t. Therefore crankshafts for marine propulsion systems, locomotives or stationary units such as generators, compressors and pumps, for example, can be induction-hardened (**Fig. 4**).

Depending on customer requirements, a choice of low-investment basic equipment or higher-level expansion stages for greatly reduced cycle times is available. Assemblies with up to six transformer-inductor units are possible, as is the operation of two separate frequency converters – which supply the power for induction – for parallel hardening of two bearings. The hardening process can be adjusted separately for all bearings and is fully automatic.

A more detailed explanation of an induction hardening process for a large crankshaft with undercut radii and the specific characteristics of this system is given below.

EXAMPLE OF USE OF ELOCRANK™ XL FOR LARGE CRANKSHAFTS

The standard hardening process for many large crankshafts continues to be surface hardening. Here only the cylindrical exterior surface of the bearing is hardened. The inductors have copper heating loops, whereby the active part is made from a single section and is predominantly effective in the area of the transverse branches. The heat-affected zone is restricted to the bearing and does not affect the area of the bearing cheeks, meaning no significant warping of the crankshaft can occur during hard-ening. Surface hardening is essentially a type of wear hard-ening with added stabilization against torsional fatigue.

Hardening of the radii together with the running face is the second method used to further strengthen the crankshaft, particularly against flexural fatigue. The inductors have to be better adapted to meet the additional hardness requirements in the radii and feature complex copper heating loops, whereby the radius-side thermal conductor branches have field concentrators. Hardening of the radii requires more power and may result in warpage of the shaft. When selecting a suitable hardening sequence, however, the amount of warpage can be reduced to a value below the grinding allowance.

Undercut hardening is a further development of hardening of the radii. Typically, workpiece geometries which have been tried and tested for many years have been used for large crankshafts, however up to now these have usually been only quenched and tem-pered and partially nitration-hardened. This is also an area where undercut hardening is applied.

As mechanical stresses on the crankshaft increase, the radii can become weak spots. However, further enlargement of the radii to reduce excessive stress is often impossible due to the reduction in the useful bearing face, with the result that the enlarged radii are 'cut in' at the expense of the cheeks. If undercut hardening is required, the inductor has to penetrate into the undercut and heat up the radius there (**Fig. 5**).

The available hardening results for undercut hardening were taken from an EloCrank™ XL with an installed MF capacity of 1,200 kW. The power is supplied by two 600 kW converters, which operate within a frequency range of 2.5-10 kHz. This power and frequency range allows operation to be adjusted to various hardening requirements.

The plant has four transformer-inductor units; two large fixed ratio transformers for good positional stability and high output, and two disc-type transformers for smaller bearing dimensions and medium output levels.

The machine allows automatic operation with up to four different inductors, such that fully automatic hardening can be performed for normal, large crankshafts without changing the inductors. The crankshaft is held in a cardan chuck on one side and rests on up to four V blocks which are adjusted in line with the hardening position by motor-operated means using the program control system.

Fig. 6a shows the hardening zone from a single-sided undercut hardening process, whereby the inductor here is initially lowered onto the bearing and then axially into the undercut. Hardening on both sides, as shown in **Fig. 6b**, requires a great deal more effort by comparison, as the thermal conductor needs to heat both undercuts.

Figs. 7a and **7b** show the position of the inductor in a workpiece (cut in order to provide a better view) and the heating process. One can see here the special

Fig. 6a: Hardening zone with single-sided undercut

Fig. 6b: Hardening zone for two-sided undercut

Fig. 7a: Position of the inductor in the undercut (component cut for this purpose)

Fig. 7b: Heating pattern of the undercut inductor

design – allowing the area of the radii to be penetrated – as well as the field concentrators for selective heating.

CONCLUSION

On the one hand, the mobilization of broad sections of the population across the world and the shortage of fossil resources, coupled with the need for long-term, low-emission technologies on the other hand, are resulting in the growing importance of modern engine designs. Their miniaturization means the demand for more compact engine components is on the rise – a trend which also affects the crankshaft.

As a result, the specific stresses of these types of crankshaft are increasing too, such that more and more importance is being attached to induction hardening of the bearings. For process-related reasons, induction rotational hardening has been adopted by all engine builders, as it allows them to achieve reproducible quality results cost-effectively. This is based essentially on the precisely controlled coordination of both sub-processes for producing a homogeneous martensitic material structure: austenitization of the bearings and selective quenching.

In addition to the variety of types of crankshaft for automotive use, more and more importance is being placed on large crankshafts for stationary and mobile applications on land and sea, as these heavy-duty engines are being used in many cases for the resource-efficient transportation of vast numbers of people and goods. In future the conventional 2-stroke diesel units in sea vessels will likely be replaced by modern gas engines which, in turn, will mean greater demands being placed on the strength of the crankshafts due to the specific ignition characteristics something which can be achieved through induction rotational hardening.

In this way, the process of induction hardening of the bearings, with or without undercut radii, will make an important contribution to the eco-friendly mobilization of the world's population.

LITERATURE

[1] Dappen, S.; Amiri, F.: Verzugsminimiertes Induktionshärten von Kurbelwellen, elektrowärme international, Issue 3, 2008, page 167-170.

[2] SMS Elotherm Patent EP 0 427 879 B1, Vorrichtung und Verfahren zum induktiven Erwärmen von Werkstücken.

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