
Elimination of straightening operation in induction hardening of automotive camshafts

Gary Doyon, Valery Rudnev*, John Maher,
Randall Minnick and Glen Desmier

Inductoheat Inc.,
An Inductotherm Group Company 32251 N. Avis Dr.,
Madison Heights,
Michigan 48071, USA
Email: garyd@inductoheat.com
Email: rudnev@inductoheat.com
Email: jmaher@inductoheat.com
Email: rjm@inductoheat.com
Email: gcd@inductoheat.com
*Corresponding author

Abstract: Recent technological breakthroughs in induction surface hardening of camshafts dramatically reduce their distortion. Achieving almost undetectable camshaft distortion and, in many cases, an elimination of an entire straightening operation is the result of three factors: an ability to form a true uniform hardness pattern, minimisation of maximum pick temperature and avoidance of applying any pressure/force during hardening. Other benefits of utilising the SHarP-C™ Technology in recent installations have proven to produce not only superior straightness but also better metallurgical properties of induction hardened lobes and bearings. This advanced technology also minimises energy consumption and substantially increases inductor life.

Keywords: camshaft; hardening; induction; coil; distortion; straightening; inductor; heat treating; cracking.

Reference to this paper should be made as follows: Doyon, G., Rudnev, V., Maher, J., Minnick, R. and Desmier, G. (2016) 'Elimination of straightening operation in induction hardening of automotive camshafts', *Int. J. Microstructure and Materials Properties*, Vol. 11, Nos. 1/2, pp.119–133.

Biographical notes: Gary Doyon is a Chairman/CEO of Inductotherm Group. He began his career with Thermatool Group, which was comprised of five companies at the time being also part of the Inductotherm Group. He held various positions including vice president of sales and vice president of operations. Then, in 2001, he was asked to take over the Inductoheat Group and the Thermatool Group. In 2005 he was promoted to be a Chairman/CEO of Inductotherm Group that is made up of more than 40 companies located around the world. His credits include numerous patents and engineering publications.

Valery Rudnev is a Group Director of Science and Technology of Inductotherm Group (induction heating and heat treating applications) and Chairman of Technical Committee of Forging Industry Association (FIA). In 2006, he was elected as a Fellow of the ASM Int'l in recognition of his distinguished

contributions to the field of materials science and materials engineering. His credits include more than 40 patents and inventions (US and International) and more than 200 publications.

John Maher is a Vice President – OEM of Inductoheat, An Inductotherm Group Company. Western Michigan University (WMU) Graduate – Business (Industrial Marketing) & Manufacturing Technology. He has more than 25 years of experience delivering solutions in the automotive, aerospace and heavy equipment industries. In the past, he was President of Artis Systems, Marketing Manager of Marposs Corporation, and Business Manager of Axson North America.

Randall Minnick is Vice President – Engineering at Inductoheat, Inc., an Inductotherm Group Company. He joined Inductoheat in 1993 as a Mechanical Design Engineer. He has held various positions throughout his tenure with Inductoheat including Project Engineer, Engineering Director of Mass Heating Division, and Vice President – Engineering of Inductoheat (presently). Besides managing various departments, he specialises in Crankshaft, Camshaft, and Stress Relieving heat treating processes. He has more than 20 years experience in the induction heating technologies.

Glen Desmier is a Project Manager (crankshaft and camshaft hardening technologies) of Inductoheat Inc., An Inductotherm Group Company. He received his BSME from Mysore University, India and MSME from Ohio University, USA. His concentration is Product standardisation and development, 3-D CAD of electro-mechanical systems, R&D, inductor, tooling design, and assistance in implementing novel technologies. Among his credits are 2-patents, 9-engineering publications and several awards.

This paper is a revised and expanded version of a paper entitled ‘New technology straightens out camshaft distortion’ presented at *Inductoheat’s Customer Conference*, Madison Heights, Michigan, 11–12 March, 2015.

1 Introduction

Electromagnetic induction is a popular method for heat treating a variety of automotive components including camshafts. Camshafts belong to a group of irregularly-shaped parts consisting of several sets of cam lobes and bearings. The number of lobes, their size, profile, positioning and orientation are dependent upon the camshaft type, engine specifics and can vary to great extent (Figure 1).

A good combination of hardness, wear resistance and strength is essential for cam lobes. Besides that it is also imperative to have compressive residual stresses on working surfaces of lobes and bearings. Those stresses help to prevent a premature crack initiation and propagation thus enhancing contact fatigue life and camshaft durability.

In not so frequent cases, alternative heat treatment processes (for example, carburising, laser hardening and others) are used for hardening working surfaces of camshafts. However, in the great majority of applications, electromagnetic induction is a preferable choice for camshaft hardening due to several measurable process benefits. These include but are not limited to Doyon et al. (2014a, 2014b):

- Overall cost effectiveness, high production rates and space savings (small footprint).
- Environmental friendliness, considerable reduction to heat exposure and advantages in safety (neither combustion nor unfriendly environments are used).
- High energy efficiency and the ability to provide selective heating of the surface areas where phase transformation is required. Short startup and shutdown times. No energy is needed to build or maintain the heat in non-operative conditions of the hardening equipment.
- Piece-by-piece processing with individual component traceability, superior metallurgical characteristics, high product quality and repeatability.

In addition to good strength and wear resistance, camshafts need to be straight to offer vibration free and quiet performance. Depending upon engine specifics, typical camshaft distortion after applying conventional induction surface hardening processes is within 30–90 μm range and can even be greater in some cases. This is the reason why the heat treatment of the camshafts is followed by straightening and grinding/polishing stages. During those stages, the roughness of camshaft working surfaces is minimised and dimensional accuracy of an entire camshaft is ensured.

Figure 1 Examples of diversity of geometries of automotive camshafts required to be induction surface hardened. Shape, positioning, orientation and quantity of cam lobes make a pronounced impact on design specifics of induction hardening equipment (see online version for colours)



Source: Courtesy of Inductoheat Inc., *An Inductotherm Group Company*

Complex processes take place during surface grinding (Grum, 2007a, 2007b). Monitoring of grinding operations is not an easy task. Excessive heat generation due to inappropriate grinding conditions can alter the quality of the camshaft, negatively affecting its performance and the wear resistance of working surfaces by developing undesirable microstructures, causing spotted or low hardness readings, decreasing beneficial compressive residual surface stresses, and in some cases, even reversing desirable residual stress distribution. Aggressive grinding can also lead to crack development. Besides that, the amount of grinding stock that is removed from the hardened case directly affects the life of the cutting tool, process robustness and overall cost effectiveness.

Forces applied during straightening of already hardened camshafts could potentially cause cracking and inevitably lead to an appreciable reduction of desirable compressive residual surface stresses potentially compromising the performance characteristics of the camshafts.

Therefore, the minimisation of the amount of grinding stock, production of camshafts as straight as possible and elimination of an entire straightening operation are vital goals of modern technology and is the subject of the novel process discussed in this paper. Those factors are associated with the ability to produce a uniform hardness pattern along the circumference of the cam lobes and bearings as well as the minimisation of the total amount of metal being heated to elevated temperatures. It should be noted that, with the lack of symmetry, camshafts have a relatively complex geometry (Figure 1). As expected, when heating irregular-shaped components such as camshafts, a critical factor that affects shape distortion is related to the amount of the heat generation. Straightness characteristics decline with an increased amount of heated metal that is directly related with increased metal expansion/contraction (Rudnev, 2014, 2015; Rudnev et al., 2003). Unfortunately, the majority of the conventional induction camshafts hardening processes are associated with an inability to minimise a mass of heated metal and failure to achieve true uniform hardness profiles.

A new technology discussed here makes it possible to induction harden camshafts with practically undetectable distortion, maximising the formation of compressive residual surface stresses and ensuring true contour hardening patterns on camshaft lobes and bearings.

2 Review of conventional induction camshaft hardening processes

A variety of inductor designs and heating modes have been used in the past for camshaft hardening by electromagnetic induction. Specifics of a particular inductor style and process recipe depend upon the camshaft's geometry, production rate, required hardness case depth, prior microstructure, the method of material handling and some other factors.

When hardening irregularly shaped components such as working surfaces of camshafts, adjoining areas (e.g., journals) may exclude the possibility of positioning the component inside a cylindrical coil having uniform magnetic coupling. In other cases, the required coil-to-part air gap that would provide sufficient clearance for loading and unloading the camshaft is so large that it dramatically reduces coil electrical efficiency or may even prevent obtaining required hardened patterns due to an unfavourable combination of coil end effect and camshaft geometry. For example, camshaft lobes might have a relatively sharp 'nose' and greatly undersized base circle in combination with large bearings or eccentric journals.

Heat times for austenisation are typically within the 3–12 second range. Shorter heat times were used for friendlier initial structures (e.g., Q&T and normalised prior microstructures) and/or smaller differences between nose and heel diameters. Frequencies of 3 kHz to 40 kHz range are commonly applied and selection of a particular frequency depends upon the required case depth and camshaft geometry. Power requirements vary widely, being functions of lobe/journal geometry, production rate and are usually within 1.2–2.1 kW/cm² range.

Generally speaking, camshafts can be induction hardened using one of two techniques:

- scan hardening of a single lobe, or
- static or single-shot hardening of a single lobe or multiple lobes.

2.1 Scan hardening of camshafts

Scan hardening requires less power since only a portion of the single wide lobe is heated using inductors with narrow heating faces. Scan inductors also offer the greatest flexibility by allowing hardening lobes with various lengths/widths. However, low production rates associated with scan hardening limits its wide utilisation in applications requiring high output.

Other recognisable drawbacks of single-lobe scan hardening are related to known challenges in obtaining required hardness patterns on closely positioned lobes leading to measurable ‘lobe-to-lobe’ hardness pattern deviations and the undesirable tempering-back of localised regions on previously hardened lobes (Rudnev, 2014, 2015; Rudnev et al., 2003). Besides that spotted hardness readings are often observed due to spray quench back splashes on closely positioned lobes/bearings.

2.2 Static hardening of single lobe or multiple lobes with camshaft rotation

In contrast to scan hardening, static heating of an entire working surface of a single cam lobe is also used in some cases allowing increasing production rates. All lobes are progressively heat treated. This process usually requires greater coil power due to the need to austenise an entire surface of a lobe to a desirable depth for achieving the required hardness pattern upon a subsequent quenching.

Coil copper is often profiled in an axial direction to improve power density distribution and to take into consideration electromagnetic end effects. Camshafts might be rotated during induction hardening. Quenching can be incorporated into an inductor design or it can be done outside of the inductor after a completion of an austenisation cycle.

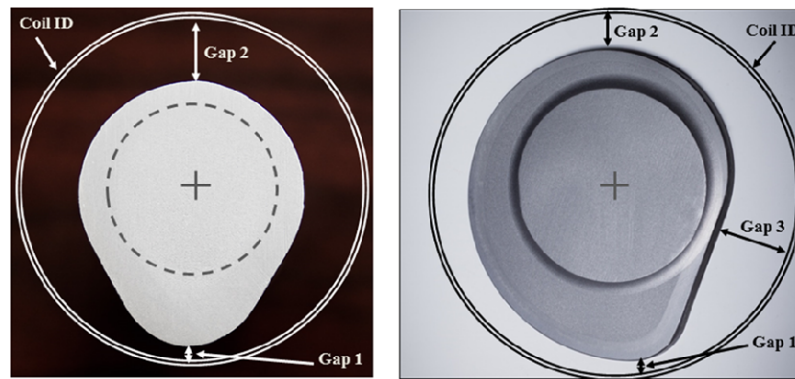
In the past, being the most popular camshaft hardening process, static or single-shot hardening with camshaft rotation is usually associated with noticeably deeper case depths in the nose of the cam lobe compared to its base circle (the heel) area because the nose has closer electromagnetic coupling with the coil current carrying surface.

As an example, Figure 2 illustrates two typical examples of a variation in electromagnetic coupling between the coil inside diameter (coil ID) and different regions of the selected cam lobes. The double solid circle indicates an inside diameter (current carrying surface) of an inductor.

Proximity effect manifests itself in localised redistribution of the electromagnetic field of the coil resulting in respected deviation of the heat generation. As an example, Figure 3 shows results of FEA computer modelling of electromagnetic field distribution in case of a single-lobe static hardening utilising a bare coil (Figure 3(A)) and coil with ‘U’-shaped magnetic flux concentrator (Figure 3(B)). Due to proximity effect, more imaginary lines of the electromagnetic field are closing their loops in air without reaching the surface of the heel of the lobe compared to its nose. This results in an appearance of areas with a temperature deficit or surplus that inevitably leads to an appearance of ‘hot’ (the nose) and ‘cold’ (the heel) regions and respected hardness case depth variation.

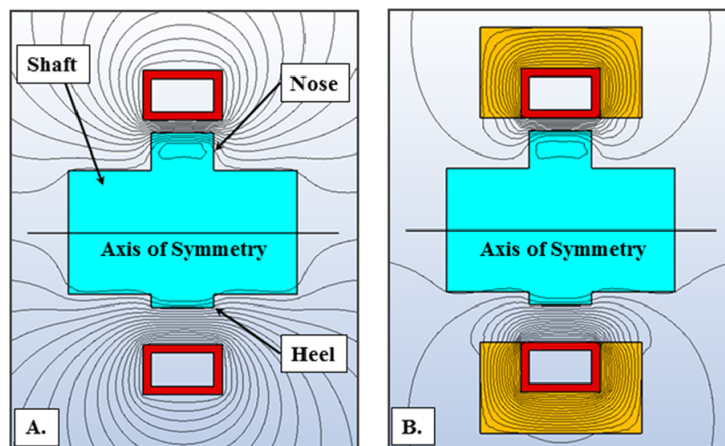
Non-uniform temperature distribution is associated with a non-uniform hardness pattern, producing noticeably greater case depth in the nose of the lobe compared to its heel. An attempt to provide a minimum required hardness case depth in the poorly coupled heel region may result in measurable overheating of the nose that could not only worsens camshaft straightness but can also produce undesirable metallurgical structures (e.g., grain coarsening, etc.) and potentially cause surface or subsurface cracking during austenisation or upon quenching.

Figure 2 Variation in electromagnetic coupling between coil inside diameter (coil ID) and different regions of the camshaft lobes (see online version for colours)



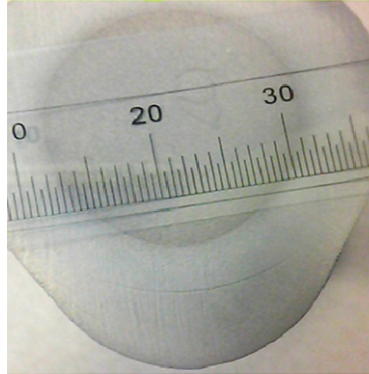
Source: Rudnev (2014)

Figure 3 FEA computer modelling of magnetic field distribution in a single-lobe hardening: (A) utilising a bare coil and (B) utilising a coil with 'U'-shaped magnetic flux concentrator (see online version for colours)



Source: Rudnev (2015)

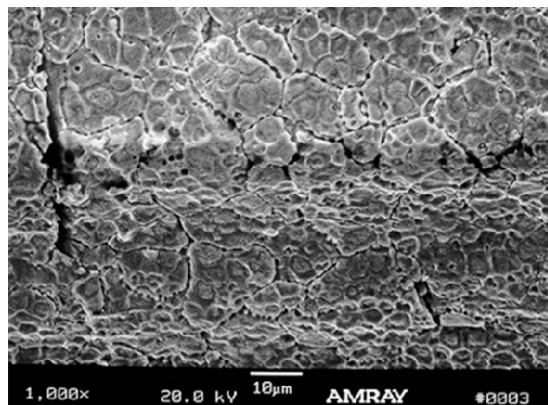
As an example, Figure 4 shows non-uniformity of the hardness depth and subsurface thumbnail-shape crack. To provide a minimum required effective case depth of 4.6 mm in the heel area, the case depth in the lobe nose is doubled, exceeding 9 mm. Such dramatically increased case depth and enlarged heat affected zone (HAZ) in the lobe nose could also alter localised residual stress distribution and could even potentially reverse it.

Figure 4 Subsurface thumbnail cracking (see online version for colours)

Source: Rudnev (2015)

Undesirable combinations of impurities, residual and trace elements, elements used in the steel making process, as well as non-metallic and intermetallic constituents could increase brittleness and crack sensitivity. Higher than desirable temperatures that occur during steel austenisation could cause adverse microstructural changes including severe grain coarsening and incipient melting (grain boundary liquation). Those changes could be associated with the loss of strength, ductility and toughness of steel increasing crack susceptibility and making components prone to intergranular cracking. Appreciable geometrical irregularities (such as 'sharp noses' of cam lobes) can further contribute to a crack initiation.

Figure 5 shows a typical SEM image of the grain boundary separation occurring due to an incipient melting of overheated medium carbon steel. Coarse grains and weakened boundaries can promote crack development during spray quenching, grinding or straightening operations.

Figure 5 SEM image of the grain boundary separation due to an incipient melting of overheated medium carbon steel

Source: Rudnev (2015)

In some cases, even seemingly insignificant increases in the hardness case depths are sufficient to initiate cracking, particularly when hardening low toughness materials such as high carbon steels, grey cast irons, etc. As an illustration, Figure 6 shows examples of subsurface cracking in the lobe region of a camshaft fabricated from steel with 0.6% of carbon content. *Note:* The crack appears regardless of a seemingly insignificant increase in the case depth in the lobe nose area.

Examples shown in Figures 4–6 emphasise an importance of obtaining true uniform hardening patterns and avoiding localised heat surplus and severe grain coarsening.

To increase output, multiple lobes can be heat treated simultaneously. A corresponding number of single-turn inductors are connected electrically in a series providing required simultaneous heating of several lobes (e.g., two or four lobes) when hardening automotive camshafts with lobes of a similar size and shape and having the same or similar axial gaps between them. Hardening of multiple lobes typically necessitates having further increased inverter output power compared to scan hardening. This is due to the need to simultaneously austenise working surfaces of multiple lobes.

Coil copper is often profiled in an axial direction to obtain desirable power density distribution, to control end effects, and to take into consideration an electromagnetic interaction between neighbouring turns and to address specifics of the geometry of the cam lobes. Camshafts are typically rotated during induction hardening. Quenching can be incorporated into an inductor design or it is done out of place after a completion of an austenisation cycle.

Figure 6 Subsurface cracking in a lobe region of a camshaft fabricated from steel with about 0.6% of carbon content. *Note:* crack appears regardless a seemingly insignificant increase in the case depth in the lobe nose area (see online version for colours)



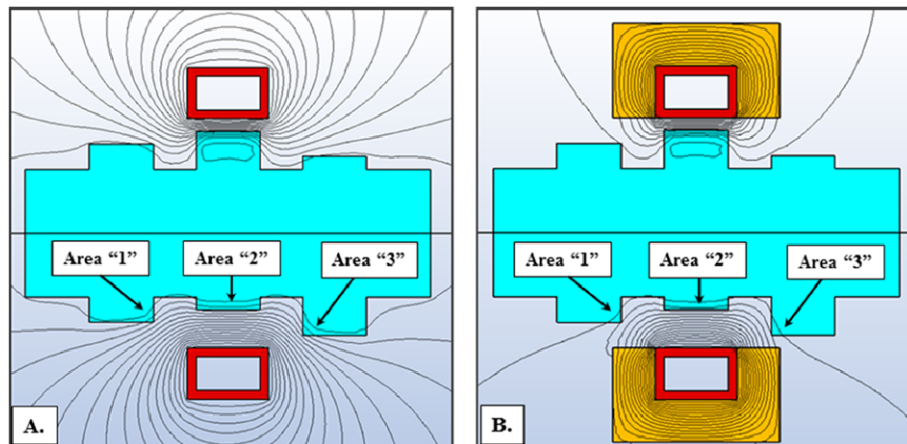
Source: Rudnev (2015)

Besides considerably non-uniform hardness pattern along the circumference of the heat treated lobes and the possibility of crack development, one of the major problems that is associated with conventional induction hardening of camshafts with closely positioned lobes and journals is related to undesirable heating of adjacent areas that have previously been hardened (so-called temper back effect). The complexity of this problem arises from the facts that, due to external electromagnetic field propagation, the eddy currents are induced not only in the camshaft area that is encircled by an inductor, but in adjacent regions as well.

A magnetic field spreads around an induction coil and links with electrically conductive surroundings, which could include neighbouring regions of the camshaft (including adjacent cam lobes and journals) and possibly certain areas of the machine or fixtures. As a result of induced eddy currents, heat will be produced. This heat can cause undesirable metallurgical changes in edge areas of the camshaft lobes that were hardened in a previous process stage. To illustrate this, Figure 7(A) shows the results of FEA computer modelling of coil field distribution in camshaft single-lobe hardening with closely-positioned lobes. Due to poor electromagnetic coupling in the heel area of the middle lobe (Area '2') and the necessity to provide sufficient austenitisation, there will be significant heat generation in neighbouring lobes (Area '1' and, in particular, Area '3') (Lupi and Rudnev, 2014). Corners of neighbouring lobes are particularly susceptible for undesirable temper-back of previously hardened regions or even their re-hardening (Figure 7(A)).

A much smaller portion of the external field links with adjacent lobes outside the coil when a 'U' shaped magnetic flux concentrator is warped around the hardening inductor (Figure 7(B)). Depending upon a camshaft's geometry, this can noticeably reduce power density induced at the corners and edges of neighbouring lobes compared to using a bare coil (Figure 7(A)). Unfortunately, in some cases this reduction might not be sufficient to eliminate the above-discussed undesirable phenomena.

Figure 7 Results of FEA computer modelling of coil field distribution in camshaft single-lobe hardening with closely-positioned lobes. (A) Corners of neighbouring lobes are particularly susceptible for undesirable temper-back of previously hardened regions or even their re-hardening utilising a conventionally designed bare coil and (B) a much smaller portion of the external field links with adjacent lobes outside the coil when a 'U' shaped magnetic flux concentrator is warped around the hardening inductor. Unfortunately, in some cases this reduction might not be sufficient (see online version for colours)



Source: Rudnev (2015)

2.3 Conventional static (non-rotational) hardening inductors

Recognising the obvious benefits of the non-rotational hardening process, several attempts were made over the years to develop such technologies. With static hardening, both the inductor and camshaft are motionless during the heating and quenching stages.

Conventional single-turn coils were one of the earliest inductors to surface harden camshafts. The cam lobe was properly positioned/oriented in the inductor. Laminations or powder-based magnetic composite materials were applied only to the coil in the lobe heel area as an attempt to compensate for the deficit of the heat sources due to poor ‘coil-to-lobe’ electromagnetic proximity there. Unfortunately, this design resulted in poor controllability of the hardness pattern, low heating efficiency, high camshaft distortion and does not eliminate undesirable temper-back, thus its use is extremely rare nowadays.

2.4 Clamshell or split inductors

Specially designed clamshell or split inductors are also used for non-rotational hardening of camshafts (Doyon et al., 2014a; Rudnev et al., 2003). Coil copper is profiled to accommodate the shape of the cam lobe. Clamshell inductors are so named because they are typically hinged on one side so that the camshaft can be loaded in the correct heating position maintaining a uniform air gap between the heating face and lobe surface. This helps to form a uniform hardness pattern, apply short heat times and dramatically minimise the lobe distortion. Unfortunately, the short life of clamshell inductors (<10,000 cycles), poor reliability and maintainability due to electrical contact issues are some of the main drawbacks that dramatically restrict their utilisation in high production environments.

3 Advanced technology

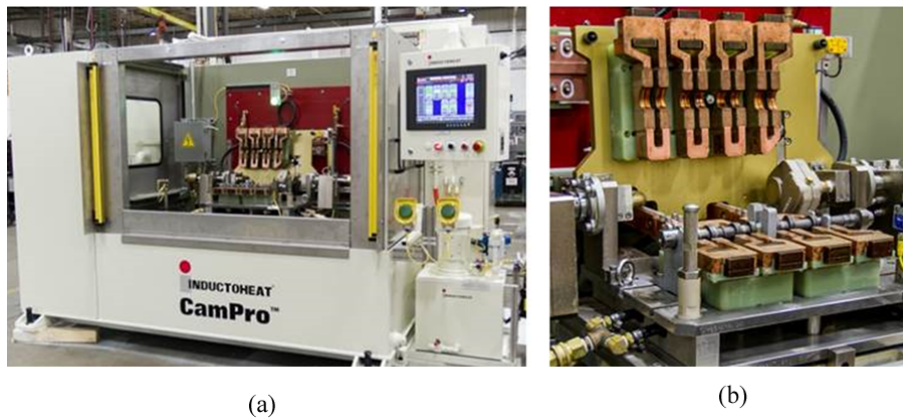
Patented non-rotational technology (SHarP-CTM Technology) was developed for induction hardening of crankshafts and has recently been expanded for producing a true contour hardening of camshafts (Doyon et al., 2014a, 2014b; Loveless et al., 2001; Rudnev and Loveless, 2005; Doyon et al., 2012). Figure 8(a) shows a CamProTM machine that utilises SHarP-CTM Technology. Abbreviation SHarP-C is an acronym for surface hardening process for crankshafts and camshafts.

High-production SHarP-CTM induction system consists of a number of top (passive) inductors and correspondent set of bottom (active) inductors (Figure 8(b)). The bottom inductors (being active and connected to a power supply) are stationary, while the top (passive) inductors represent electrically close-loop systems. While being unpowered, top inductors can be opened and closed during camshaft loading and unloading. Each inductor has profiled areas where the cam lobes to be heat treated can be located, while the top inductors being unpowered are in an ‘open’ position (Figure 9, top). Due to the ‘active/passive’ approach, electrical contact issues associated with clamshell coils are not a problem here because there is no breakage of the path for electrical current flow.

Following loading of the camshaft into the heating position, the top inductors pivot into a ‘closed’ position and the power is applied from the power supply(s) to the bottom set of (active) inductors. The electrical current flowing in the bottom inductors (Figure 9, top) will instantly induce the eddy currents that start flowing into the top set of inductors thanks to a set of lamination packs that serve as magnetic flux couplers allowing the top and bottom inductors to be electromagnetically coupled similar to the effect of a

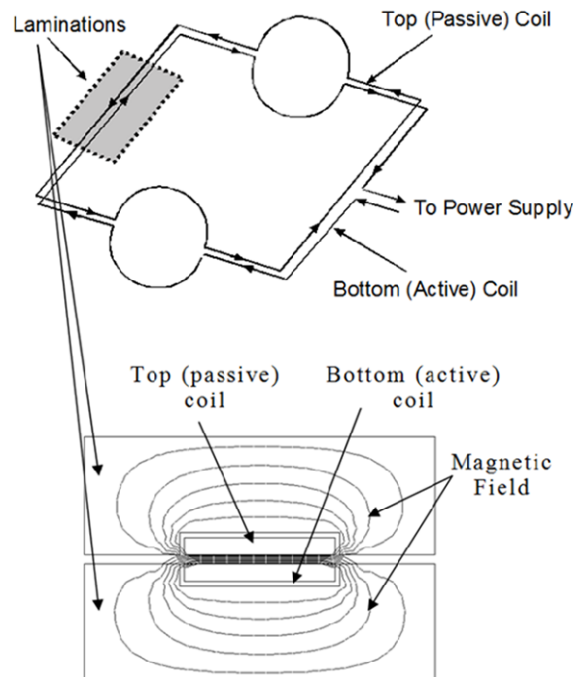
transformer (Figure 9, bottom). Therefore, cam lobes ‘see’ the SHarP-C™ inductor as a classical encircling and highly electrically efficient induction system that provides good electromagnetic coupling with a uniform ‘lobe-to-inductor’ gap.

Figure 8 (a) CamPro™ machine that utilises SHarP-C™ Technology and (b) close-up of inductor design. Depending upon required case depths, frequencies of 10–30 kHz range are typical. Power range depends upon process specifics (i.e., production rate, lobe geometry, etc.). Cycle time 32 s per a camshaft (based on 1.5 litre and 2.0 litre diesel or regular fuel engines) (see online version for colours)



Source: Courtesy of Inductoheat Inc., An Inductotherm Group Company

Figure 9 Circuit of non-rotational SHarP-C™ Technology (top) and magnetic coupling of top and bottom inductors (bottom)



Source: Rudnev et al. (2003)

With the SHarP-CTM Technology, commonly used uniform lobe-to-inductor' air gaps/clearances are within 3–4 mm range. This helps to minimise the energy consumption. In contrast, typical air gaps/clearances of conventional inductor designs (Figures 3 and 7) are substantially non-uniform and commonly vary from 3 mm to 12 mm (the lobe nose area vs. heel region). As expected, these variations negatively affect energy consumption, hardness pattern uniformity and achieved pick temperatures.

If required, the copper heating face of the SHarP-CTM inductors can be easily and individually profiled to further compensate for the geometrical irregularity of sharp noses of cam lobes. This helps to achieve desirable hardness patterns and produce truly uniform hardness case depth distribution.

The difference between an electrical current flowing in an active inductor (source current) and inductively generated current flowing in a passive inductor does not typically exceed 3% and can be easily compensated for by slight coil copper profiling. To equalise the heating effect of top and bottom inductors, it is usually sufficient to provide a 'passive inductor-to-lobe gap' on 0.25–0.4 mm smaller compared to a gap between 'active inductor-to-lobe'. Specially designed quench slots are used to accomplish the process of quenching as well as coil copper cooling.

SHarP-CTM process lends itself to hardening multiple lobes simultaneously (Figure 8); therefore, high production rates can be achieved.

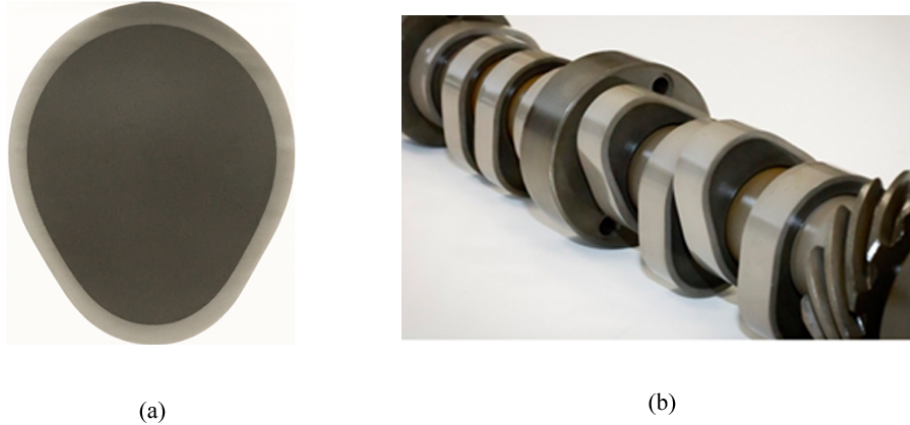
4 Achieving almost undetectable camshaft distortion and elimination of straightening operation

To obtain a proper austenisation of the loosely electromagnetically coupled heel region, conventional camshaft hardening processes are commonly associated with the necessity to increase the heating time. SHarP-CTM Technology eliminates this necessity resulting in measurable reduction of the heat time (up to 35% and even higher in some cases depending upon camshaft material and specifics of its geometry). Besides reduced energy consumption, this contributes greatly and positively in achieving superior metallurgical properties, by a dramatic reduction of achieved pick temperatures during austenisation, elimination of grain boundary liquation (incipient melting), and formation of fine grained martensitic structures. As an example, Figure 10(b) illustrates an achieved uniform case depth of closely-positioned cam lobes using inductors that are capable of providing uniform coil-to-lobe gaps and short heat times.

A measurable advantage revealed by installations that implement this patented process deals with its ability to harden camshafts with practically undetectable distortion minimising grinding stock and, in some cases, eliminating the necessity of a subsequent straightening operation.

Shape distortion of heat treated components is affected by a number of factors. The specifics of the camshaft's geometry, magnitude of processing temperatures, quenching specifics and uniformity of hardness pattern are among the most critical factors affecting distortion. Camshafts have relatively complex geometry with a lack of symmetry (Figure 1). Therefore, excessive heat generation is inevitably associated with larger and unequal metal expansion/contraction, which in turn causes greater shape distortion (Doyon et al., 2014a, 2014b; Grum, 2014; Ferguson and Li, 2014). Thus, the capability of SHarP-CTM Technology in producing true uniform hardness patterns (Figure 10(a)) makes this process highly attractive.

Figure 10 Illustration of obtaining true contour hardening patterns: (a) on closely-positioned camshaft lobes and (b) using inductors that are capable of providing uniform coil-to-lobe gaps and short heat times (see online version for colours)



Source: Courtesy of Inductoheat Inc., An Inductotherm Group Company

The core of the cam lobe remains relatively cool during the entire heating cycle (typically 2–4 s) acting as a shape stabiliser. In contrast to alternative processes where axial pressure is applied to rotate a camshaft, there is not any force applied to a camshaft during its heat treating. The camshaft is simply being rested on V-shaped blocks.

It would be appropriate at this point to provide a testimonial of one of the users of this process, which could be considered as an objective assessment of SHarP-C™ Technology, quantifying its benefits based on obtained real-life records. Ignacio Castro from Arbomex SA de CV commented (2014),

“The SHarP-C hardening machine helped us to reduce the camshaft’s distortion down to 3–5 microns and we have been able to eliminate the entire straightening operation. So, our savings on elimination the straightening operation alone is about \$40,000 per year. On top of that there has been substantial improvement in the quality of the hardened camshafts, and our scrap was reduced about 1.5%.”

5 Future development

Until recently, oven/furnace tempering has been used almost exclusively for the tempering of camshafts after hardening. The use of induction heating for tempering of hardened camshafts was limited due to the known difficulties in providing a sufficiently uniform heat source generation, occurring due to the above-discussed limitations of presently used induction processes. Since tempering temperatures are always below the Curie point, the steel is always magnetic and skin effect is highly pronounced. This worsens localised heat non-uniformities at tempering temperatures while using conventional induction systems.

The ability of SHarP-C™ Technology to provide tightly-coupled and uniform ‘lobe-to-inductor’ gaps and obtaining true uniform heat distribution along the circumference of the heated lobes, suggests re-evaluating the possibility of using induction tempering in camshaft heat treating applications. Thus, the same system could

potentially offer induction hardening and tempering of camshafts as it has been successfully used for a number of years in heat treating of crankshafts. Future research work is needed to carry out a feasibility study in this respect.

6 Conclusion

The compound benefits of patented SHarP-CTM Technology include the following major points:

- Achieving almost undetectable camshaft distortion being about 3–5 microns (based on 1.5 l and 2.0 l diesel or regular fuel engines) and, in many cases, an elimination of an entire straightening operation is the combined result of three factors:
 - 1 the ability to form a true uniform hardness pattern
 - 2 reduction of pick temperatures during austenisation
 - 3 avoidance of applying any pressure/forces during camshaft hardening.
- Experience of using SHarP-CTM camshaft hardening technology reveals producing not only superior straightness but also better metallurgical properties of induction hardened camshafts forming fine grain martensitic structures and minimising a probability of crack development and grain boundary liquation due to an improvement in temperature uniformity along the cam lobe surface and minimisation of pick temperatures.
- The energy consumption during both: heating and cooling was reduced. Depending upon the specifics of the camshaft's geometry and heat treat specifications, combined savings on energy consumption may exceed 12–18% depending upon material, case depth, camshaft shape, size, topology and topography compared to presently used processes.
- In 2015–2016, an automotive industry has dramatically increased the savings targets expecting 6–8% reduction (Ghosn, 2014). Besides that, some car manufacturers set ambitious goals to reduce development costs as much as 40% and reduce spending on parts more than 20% by 2020 (Ghosn, 2014). The implication for the supplier community is clear – maintaining business at OEMs will require additional cost reductions and developing of new technologies such as one discussed in this paper can assist to accomplish this goal.

References

- Doyon, G., Loveless, D., Brown, D., Rudnev, V., Boussie, T. and Desmier, G. (2012) *Induction Heat Treatment of Complex-Shape Workpieces*, US Patent # 8,222,576, 17 July.
- Doyon, G., Rudnev, V. and Maher, J. (2014a) 'Induction hardening of crankshafts and camshafts', in Rudnev, V. and Totten, G. (Eds.): *ASM Handbook, Vol.4C: Induction Heating and Heat Treating*, ASM Int'l, Materials Park, Ohio, USA, pp.172–186.
- Doyon, G., Rudnev, V., Maher, J., Minnick, R. and Desmier, G. (2014b) 'New technology straightens out camshaft distortion', *Industrial Heating*, Vol. 12, December, pp.46–52.

- Ferguson, B.L. and Li, Z. (2014) 'Modeling and simulation of stresses and distortion in induction hardened steels', in Rudnev, V. and Totten, G. (Eds.): *ASM Int'l*, pp.272–290.
- Ghosn, C. (2014) 'Renault-Nissan raises savings targets in cooperation push', *Automotive News*, 30 January, 2014 (Accessed 3 May, 2015).
- Grum, J. (2007a) 'Influence of various induction-heating and grinding conditions on residual stress profiles', *Int. J. Microstructure and Materials Properties*, Vol. 2, No. 3–4, pp.310–325.
- Grum, J. (2007b) 'Overview of residual stresses after induction surface hardening', *Int. J. Materials and Product Technology*, Vol. 29, Nos. 1–4, pp.9–42.
- Grum, J. (2014) 'Residual stresses in induction hardened steels', in Rudnev, V. and Totten, G. (Eds.): *ASM Handbook, Vol.4C: Induction Heating and Heat Treating, ASM Int'l*, pp.103–129.
- Loveless, D., Rudnev, V., Lankford, L., Desmier, G. (2001) *Induction Heat Treatment of Complex-Shape Workpieces*, US Patent # 6,274,857, 14 August.
- Lupi, S. and Rudnev, V. (2014) 'Principles of induction heating', in Rudnev, V. and Totten, G. (Eds.): *ASM Handbook, Vol.4C: Induction Heating and Heat Treating, ASM Int'l*, pp.6–27.
- Rudnev, V. (2014) *Invited Lecture on Induction Heat Treatment of Automotive Components for Linamar Group Companies*, Guelph, Canada, 16 July.
- Rudnev, V. (2015) 'Invited lecture on aspects of induction heat treating', *Peoria ASM Chapter Meeting*, Peoria, IL, 13 January.
- Rudnev, V. and Loveless, D. (2005) *Induction Heat Treatment of Complex-Shape Workpieces*, US Patent # 6,859,125, 22 February.
- Rudnev, V., Loveless, D., Cook, R. and Black, M. (2003) *Handbook of Induction Heating*, Marcel Dekker, NY, USA, p.800.