IGBT INDUCTION HARDENING AND ITS APPLICATION IN SINGAPORE

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ABSTRACT

Induction hardening has come a long way. Whilst the vacuum tube power supply is still commonly used in industries, IGBT power supply is fast gaining industrial acceptance. In terms of power efficiency, the IGBT technology is arguably the most advanced, despite its demand for sound technical know-how on the combination of capacitances and inductances to achieve optimal effects. This paper aims to provide a brief review of the induction hardening process and the relationship of induction hardening parameters. This paper will demonstrate the importance of power density, frequency and traverse speed with particular reference to the experimental study on induction hardening of the AISI 4140 material. With these experimental data, two Master curves were achieved as an approach to ensure sound industrial treatment. This takes the form of determining the threshold requirement of power density to obtain maximum surface hardness. Finally, it will provide five case studies of industrial experiences in Singapore.

Keywords: *AISI 4140, Case Depth, Coiling, Frequency, Gear, Hardenability, Huge Part, IGBT Power Supply, Induction Hardening, Industrial Application, Microhardness Profiles, Optimum Surface Hardness, Power Density, Quenchant, Traverse Speed.*

1.0 INTRODUCTION

Induction hardening has been in the world since 1830 when Michael Faraday discovered how an electric current can induce magnetic flux and eddy current in a metallic conductor coupled to it. This breakthrough forms the basis for the induction hardening process.

Induction hardening is widely used and industrially popular particularly in the manufacturing, automotive and heavy engineering industries.(1-5) This is due to the numerous advantages it offers. Some of the more significant advantages is its rapid rate of heating-up as compared to the convection and radiation processes of heat transmission in standard furnaces. This would also mean less scaling losses, and faster startup resulting in higher productivity. The process also offers significant energy savings as power supply can be turned on or off easily without any need to maintain bulk energy inputs in the furnaces. Selective hardening can be performed on desired regions. Hence, only the desired areas need to be heated up and not the entire work piece as in conventional furnaces.

Over the last decade or so, Transitorized Solid State Power Supply is fast replacing the conventional vacuum tube power supply. It uses the Insulated Gate Bipolar Transistor technology (IGBT). The IGBT is fast overtaking the commonly-used silicon controlled rectifier technology (SCR).(6-8) Perhaps, the greatest advantage of employing IGBT power supply is its higher output efficiency as compared to the vacuum tube technology.

2.0 THEORY

2A. Fundamentals of the Induction Process

The basis of induction hardening lies in the ability to induce eddy currents in electrical conductors. A simple induction heating system consists of a coil (*inductor*) and a source of alternating current. The coil, also termed as inductor, is generally made of copper due to its favorable properties such as low electrical resistance and non-magnetism. The coil carries an alternating current surrounding the work piece to be induction hardened. The alternating current generates magnetic fields, which induce eddy current upon the work piece. These eddy currents heats up the work piece and raises the temperature beyond the transformation temperature instantly. Austenitization takes place and the structure is instantly quenched to produce martensite.

Figure 1 shows a typical induction hardening system which comprises of a power control unit, inductor unit, heat exchangers, cooling tower, distilled water system and water tanks.

2B. Parameters

There are many factors that will affect the final outcome of an induction hardening process.(9) In this paper, we will briefly discuss six main parameters. These are the power input, frequency, coil inductance (*turns*), proximity effect, dwelling time and quenching medium.

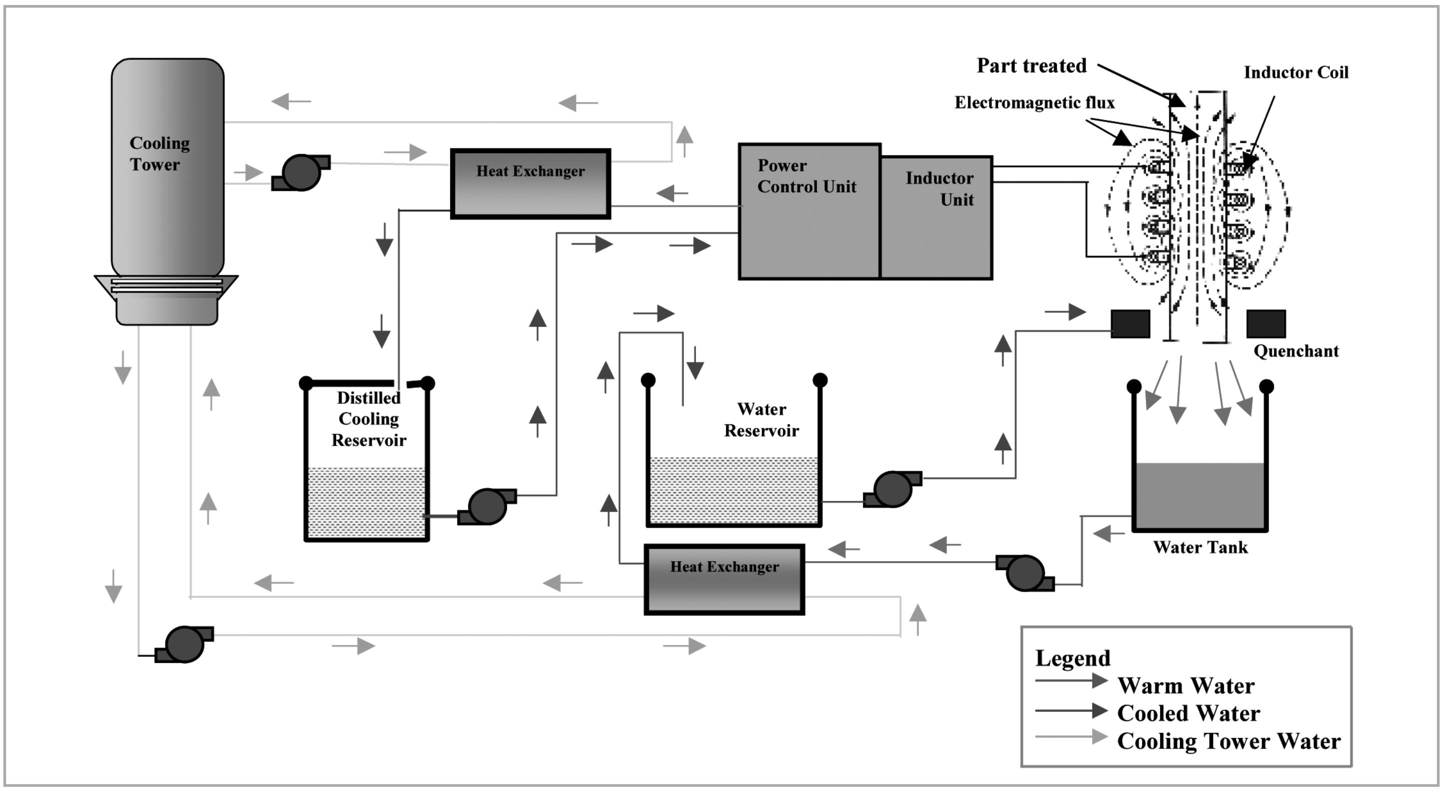


Figure 1: Schematic of a typical induction hardening system

(a) Power Input

In discussing about the power input, we prefer to consider **power density**, which is defined as the applied power divided by the surface area of the work piece.(10) As a general rule, low power density is used for through hardening to prevent overheating at the surface, whereas high power density is used for surface hardening to be achieved within the shortest possible time.

There are basically four main types of power sources: the line frequency system (*supply frequency*, 60*Hz*), motor generator system (*motor alternator*, 500*Hz* – 10*KHz*), solid-state system (*solid state inverter,* 180 – 50*KHz*) and vacuum tube (*radio frequency,* 50*KHz* – 10*MHz*). Figure 2 illustrates these four types of power sources operating at the various frequency zones for different applications. Depending on the nature of the heat treatment requirements, each system will have its unique features with distinctive advantages. Line-frequency system is used mainly in through hardening by the fact of its low operating frequency range. The efficiency of this system is high as no frequency conversion is required, hence power losses is kept to a minimum. In motor generator systems, the line-frequency current is changed to higher frequency current by electromagnetic induction using motors with copper windings. This gives a lower efficiency than the line-frequency system. The solid state system has been slowly replacing motor generator systems in the past few decades as it has lower cost and virtually no power consumption in standby mode, as compared to the motor generator system which requires 15% to 20% of maximum power consumption during standby mode. Apart from its shallow heating depth characteristic, vacuum tube system has the lowest efficiency and highest cost among the four power sources.

Choice of a power source depends primarily on frequency, although there is some overlap among frequency capabilities of the different sources. For high output power efficiency *e.g.*, the solid state power system will render better performances than the vacuum tube power system.

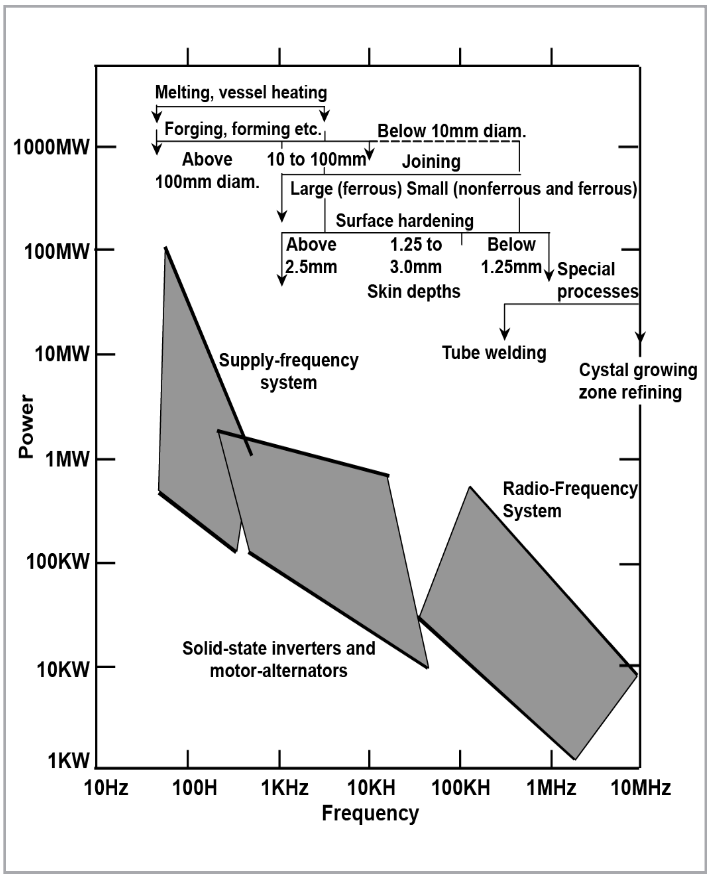


Figure 2: Different types of power sources operating at various frequency zones (11)

(b) Frequency Selection

The relationship of the electromagnetic field strength and the induced depth can be represented with Equation 1[12] :-

$$d = 5000 \sqrt{(\rho/\mu f)} \qquad \text{Equation 1}$$

where 'd' denotes the reference depth in cm, and 'f' as the frequency of the alternating electromagnetic field in hertz, 'ρ' is the resistivity of the work piece in ohm-centimeter, and 'μ' is the relative magnetic permeability of the work piece (*dimensionless*).

'd' is conventionally defined as the depth below surface at which the induced field strength and current are reduced to 37% of their surface values. As it is indicative of the skin effect of induction hardening where eddy currents are most intensive, it serves as a direct proportion of the case depth, which is normally defined by metallurgist as the case of martensitic transformation. Frequency is therefore, inversely proportional to the reference and case depths.

(c) Coiling Design

Coil design and inductance (*number of turns*) have tremendous effects on heating patterns and heat distribution. Depending on the geometry of the work piece and specification of the case depth uniformity and requirement, the inductor should be tailor-made for each application to ensure consistent and reliable treatment.[12-13]

(d) Proximity Effect

Proximity Effect refers to the air space between the work piece and the coil. This affects the heating pattern and intensities on the work piece.[10,12] For a work piece positioned close to the coil, the achievable case depth will be deeper. This is consequential of the higher power density. In this present paper, the air space between the specimens and the coil was kept as a constant to analyze the effect of the other parameters.

(e) Dwelling Time

Dwelling time has a significant effect on the work piece.[10,12] Too long a heat-dwelling time may overheat the surface resulting in melting, while too short a dwell time may not austenitize the surface to a sufficient depth. In the present experimental setup, the dwelling time was translated as the traverse speed of the specimens. Slower traverse speed would mean a longer dwelling time.

(f) Quenching Techniques and Quenchants

Quenching techniques and quenchants are important features of induction hardening. [10,12] The quenching technique used is based on the part size, geometry, hardenability of material and heating specification. Types of quenching medium include water, brine, oil, polyvinyl alcohol and polymeric solutions. The most common quenching medium used industrially is water. Oil is the preferred quenching medium for steels with high carbon content. This ensures slower cooling rates to prevent severe distortion and quench cracking. Water and brine are generally considered as severe quenchants. The cooling rate of polyvinyl alcohol solutions lies in between that of water and oil.

3.0 EXPERIMENTAL

The experiments were carried out with a 40-KW IGBT induction system. AISI 4140 specimens of Ø14 x 120 mm were induction hardened with varying parameters in power input, frequency and traverse speed as shown in Tables 1, 2 and 3. The effect of the variation of these parameters on the surface hardness and effective case depth will be discussed.

The study on the effects of rotational speed on the case depth were also carried out. However, the experimental results will be only presented in another paper. In this paper, the data presented was obtained with a rotational speed of 1.0 rev/sec.

3A Variation of Power Input

Table 1 : Parametric setup with variation in power input

Power	***8KW***	***11.6KW***	***15.2KW***	***19.2KW***	***22KW***
Fixed Parameters	Frequency 46 KHz, Traverse Speed 12.25 mm/s, Rotational Speed 1.0 rev/s				

3B Variation of Frequency

Table 2 : Parametric setup with variation in frequency

Frequency	***44KHz***	***46KHz***	***49KHz***	***52KHz***	***56KHz***
Fixed Parameters	Power 19.2KW, Traverse Speed 12.25 mm/s, Rotational Speed 1.0 rev/s				

3C Variation of Traverse Speed

Table 3 : Parametric setup with variation in transverse speed

Traverse Speed	***10.8 mm/s***	***13.8 mm/s***	***16.6 mm/s***	***19.6 mm/s***	***22.6 mm/s***
Fixed Parameters	Frequency 46 KHz, Power 19.2KW , Rotational Speed 1.0 rev/s				

For consistency of the experiment, induction hardening was started at the same reference level, 40 mm from the specimen base. The induction hardened specimens were sectioned at mid-points of the induction hardened zone. Figure 3 shows the induction hardened zone of the specimens. Table 4 shows the chemical composition of the AISI 4140 specimens.

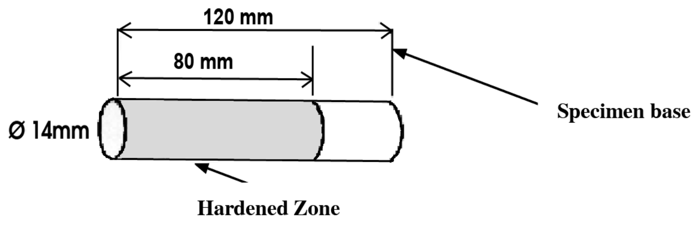


Figure 3: Specimens with induction hardened zone indicated

Table 4 : Chemical composition of AISI 4140 specimen (wt%)

	C	Cr	Mn	P	S	Si	V	Mo
AISI 4140	0.38-0.43	0.8-1.10	0.75-1.0	0.035	0.04	0.15	0.3	0.15-0.35

Induction hardened specimens were sectioned, mounted and prepared using standard metallographic techniques. Microhardness measurements were carried out using a Knoop microhardness indentor with a load of 200gmf held for 15 seconds. The metallographic specimens were etched with 3% Nital and microstructural observations were carried out at 1000 X magnification. Effective case depth is defined to be the distance from the surface where the hardness is 500HK.

4.0 RESULTS AND DISCUSSION

4A. Variation of Power Input

Table 5 shows the variation in power density and the effects in effective case depth with various power inputs, all other parameters being held constant at 46 KHz and traverse speed 12.25 mm/s. The power density is derived from the equation : Power Input / Specimen Circumference x Traverse Speed in Watt/mm^2. Figure 4 shows the microhardness profiles of induction hardened specimens.

Table 5: Variation in power density and its influence on effective case depth

Power	8 KW	11. 6 KW	15.2 KW	19.2 KW	22 KW
Power Density	14.8 W/mm	21.5 W/mm	28.2 W/mm	35.6 W/mm	40.8 W/mm
Effective Case Depth	0	0.85 mm	2.35 mm	4.50 mm	5.20 mm

The results showed that effective case depth increases with increasing power density. For the power density of 14.8W/mm^2, the surface hardness remained at 280 HK. No increase in hardness at the surface was observed. Thus, it was obvious that no martensite was formed – *i.e.*, power was insufficient to reach the transformation temperature.

With power density inputs ≥ 21.5 W/mm^2, surface hardness reached an optimum range of 650 ± 50 HK. As power density increases, effective case depth increases as more materials are raised beyond the transformation temperature.

4B. Variation of Frequency

Using a power input of 19.2 KW and a traverse speed of 12.25 mm/sec, frequency was varied to study its effects on case depth. Consistent with equation 1, case depth increases with decreasing frequency. Of noteworthy, is the observation that the surface hardness range maintained at optimum range of 650 ± 50 HK. Thus, the surfaces were all fully austenitized.

Table 5: Variation in frequency and its influence on effective case depth

Frequency	56KHz	52KHz	49KHz	46KHz	44KHz
Effective Case Depth	3.00mm	3.00mm	4.05 mm	4.50mm	5.80mm

Frequency relates to the "*skin effect*", the depth of which is inversely proportional to the square root of the frequency[11]. The thickness of the skin however, is directly linked to the case depth. Hence, as frequency decreases, it will produce a thicker skin effect that generates a deeper case depth, as indicated in Figure 5.

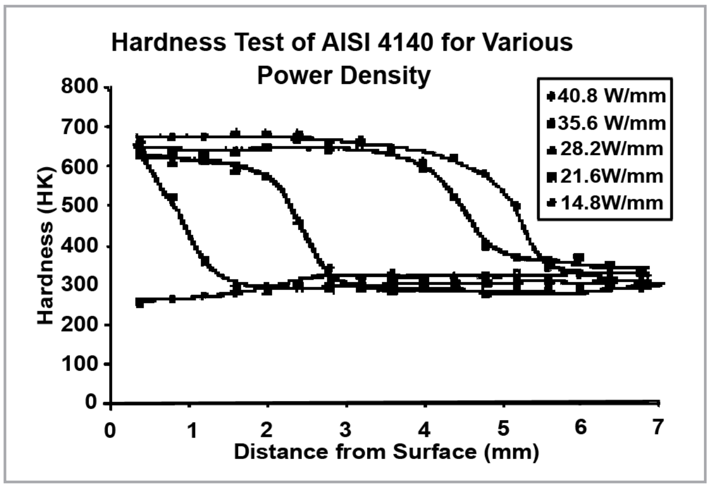


Figure 4 : Micohardness profiles at various power densities

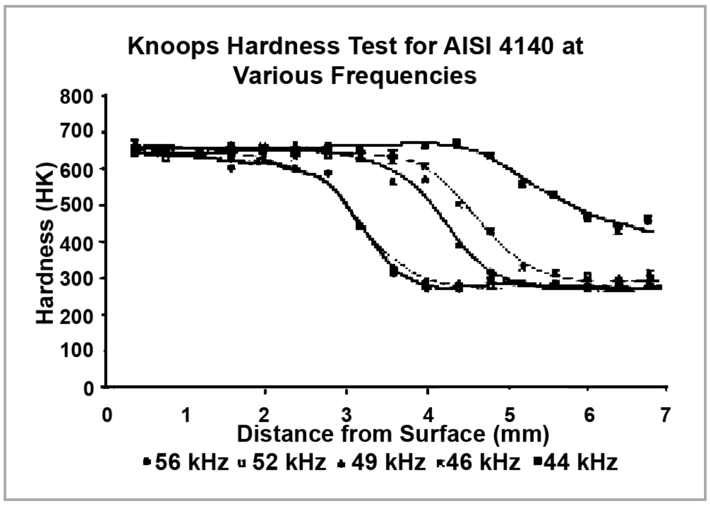


Figure 5 : Micohardness profiles at various frequencies

4C. Variation of traverse speed

Table 6 shows the results obtained by variation in traverse speed with fixed settings of 19.2 KW and 46 KHz. The effective case depth reduces as the traverse speed increases. No hardening effect is observed on the test sample surface with a traverse speed of 22.6 mm/s. This was much attributed to the short dwelling time as a result of high traverse speed such that the surface is unable to achieve the austenitizing temperature during the heating process.

Conversely, the test sample that was treated at a slower traverse speed of 10.8 mm/s has resulted in hardening throughout the entire core.

Table 6: Variation in traverse speed and its influence on effective case depth

Traverse Speed	10.8 mm/s	13.8 mm/s	16.6 mm/s	19.6 mm/s	22.6 mm/s
Effective Case Depth	7 mm	2.75 mm	1.40 mm	0.55 mm	0

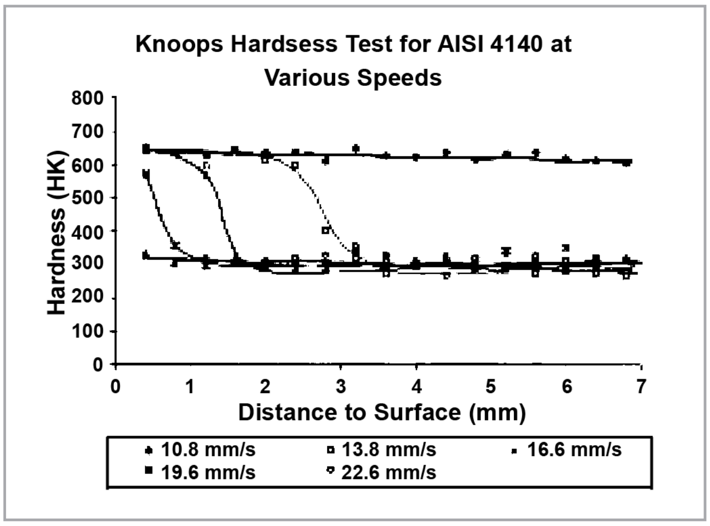
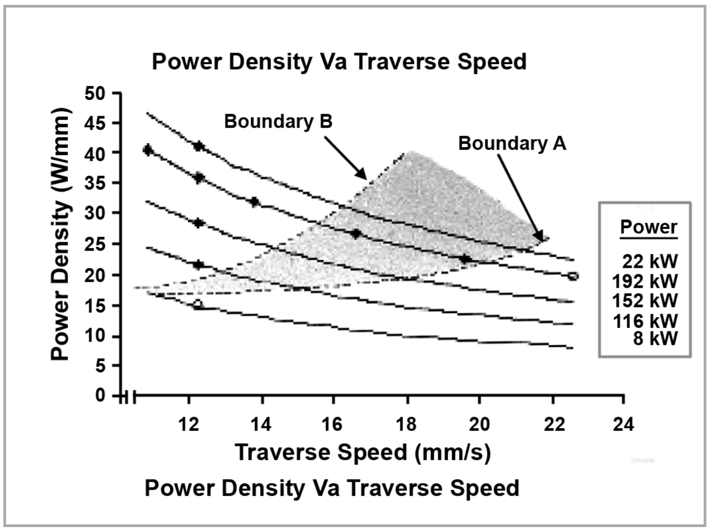


Figure 6 : Micohardness profiles at various traverse speeds



♦*Denotes hardened Surface* o *Denotes non hardened surface*
Figure 7 : Master curves for the induction hardening of Ø14 diameter shaft of AISI 4140 materials

4D. Master Curves

Power density input is related to the traverse speed of the specimen. For a given power input, the power density increases as traverse speed decreases. It is defined as the power input over surface area of specimen per unit time. Industrially then, it is advantageous to link the power density generated to the traverse speed and the power input.

Figure 7 shows a family of curves that were extrapolated from the experimental data with two Master curve boundaries A and B derived. The Master curves can help an operator to ensure sufficient power density input for austenitization to take place. Below boundary A, no hardening will occur as power density input will be insufficient to reach the transformation temperature. Optimum surface hardness range of 650 ± 50 HK is achievable only with parameters beyond boundary B.

When parametric settings between the two boundaries as indicated in the shaded region are used, partial formation of martensite takes place and maximum surface hardness is not realizable.

5.0 INDUSTRIAL CASES

In Singapore, there are numerous in-house facilities for induction heating designed specifically for mass production. These are normally of the vacuum tube power supplies that are known for their easy operations albeit poor power efficiencies. There are reports that power efficiency can be as low as 50%. In 1994, Doxon Engineering acquired an IGBT power supply to serve an American MNC. This proves to be viable and versatile. With sound technical know-how and good quality assurance practices, various material grades such as medium to high carbon steels, low-alloy steels and martensitic stainless steels can be effectively case hardened. To date, the Company has served more than 50 Clients, covering over a broad spectrum of industries to include the automotive, manufacturing, precision, marine and heavy engineering. With the aid of automation, flux intensifiers and coil design know-how, a broad range of engineering components were successfully induction hardened with minimum dimensional distortion and quench cracking. Here are but five examples:

5A. Shafts

Figure 8 shows a crate of shafts of AISI 4140 material with a hardness of about 30 HRC. In this instance, the induction hardening was carried out on one side of the shaft only. Herein is a powerful advantage of selective induction hardening over the conventional hardening process in standard furnaces. An effective and consistent case depth of 1.2 mm with a hardness of 42 – 47 HRC was specified and achieved. Figure 9 shows its typical microhardness profile.

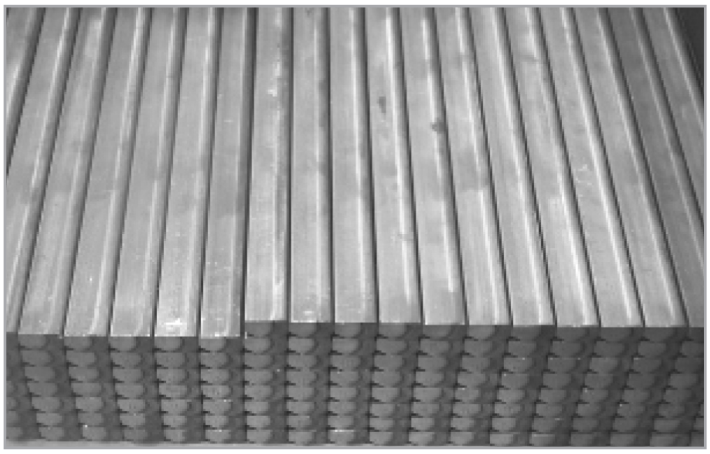


Figure 8: Induction hardened shafts

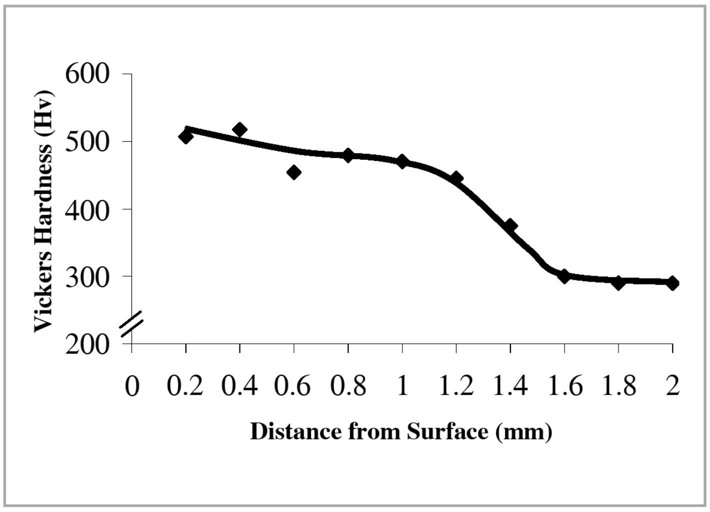


Figure 9: Microhardness profile of Shaft

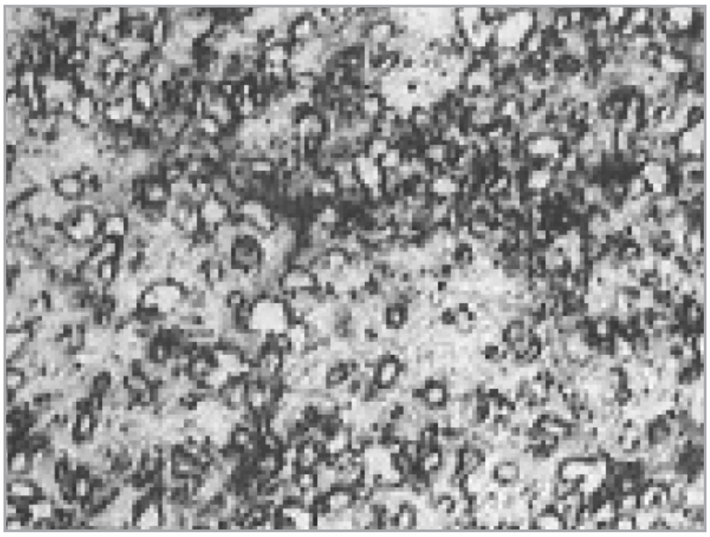


Figure 10 : Microstructure of AISI 4140 shaft. (1000 X Magnification)

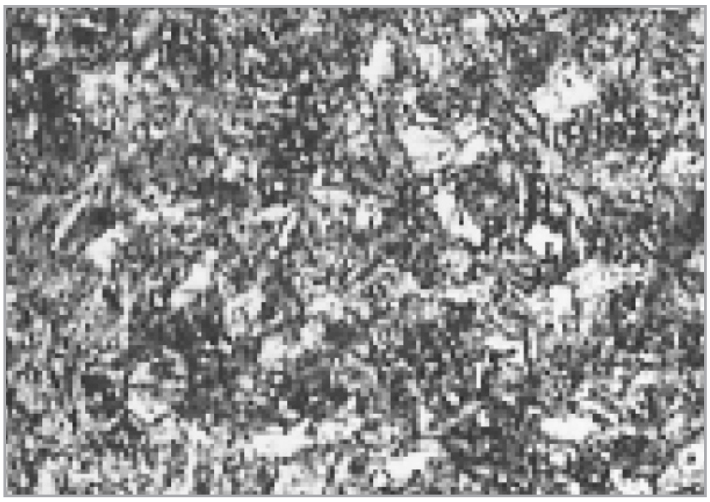


Figure 11 : Microstructure of induction hardened AISI 4140 shaft. (1000 X Magnification)

Figure 10 shows the microstructure of the shaft at 1,000X magnification. It consists of spheroidal carbides in a ferritic matrix. Figure 11 shows the corresponding tempered martensitic structure of the case with some retained austenites.

5B. Heavy Engineering Rollers

Figure 12 shows AISI 4140 rollers of outer diameter 940 mm and inner diameter 360 mm. The height measures about 280 mm and the component weighs some 650 Kg. When vacuum hardened, the rollers exhibited severe quench cracking as shown in Figure 13.

The component was successfully induction hardened at Doxon to a depth of 1.0 to 2.0 mm with 40 to 50 HRC. No cracking was observed and dimensional tolerances fell well within engineering specifications. This particular case highlights the possibility of induction hardening as a viable alternative to vacuum hardening of huge engineering parts.

Figure 12: Induction Hardened Rollers

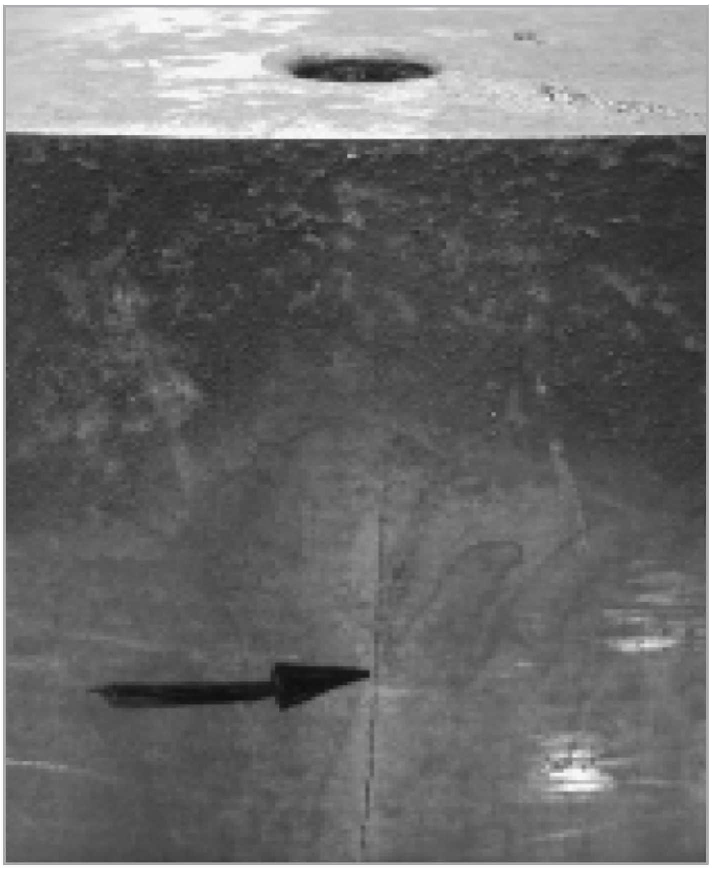


Figure 12: Induction Hardened Rollers

5C. Sprocket Gears

Figure 14a and 14b shows AISI 4140 sprocket gear hubs and shafts with gear teeth of PCD diameters 250 by thickness 50 mm to be induction hardened. The gear profile was treated to a surface hardness range of 45 to 50 HRC with a uniform case depth range of 1 to 2 mm. Figure 15 shows the cross section of the hardened layer obtained after induction hardening.

Figure 14a: Induction hardened sprocket gear hub

Figure 14b: Induction hardened sprocket gear shaft

5D. Elevator Segment

Figure 16 shows the induction hardened elevator segments used for the elevator chain. The material grade is AISI 1045. The induction hardening treatment was localized on the teeth portion of the elevator segment. Surface hardness range and case depth of 40 - 45 HRC and 0.8 - 1.5 mm were achieved respectively. Treatment at other portion particularly the two inner holes of diameter 7mm were avoided to ensure overall toughness in the elevator chain system.

Figure 16 Mass production loads of the elevator segments

Figure 17 Treatment at the inner hole of the taper holder

5E. Taper Holder

Figure 17 shows a taper holder assembled in production machineries. Induction hardening at the inner taper surface and internal diameter of the taper holder was effectively processed with an integrated coiling and fixturing design. The material grade of the holder is AISI 4340. Surface hardness range and case depth of 45 - 52 HRC and 1 - 1.5 mm were achieved respectively.

6.0 CONCLUSION

The experimental results showed the influence on effective case depth with variation in power input, frequency and traverse speed during the induction hardening process. Effective case depth increases with increasing power density, decreasing frequency and traverse speed.

From the results, obtainable optimum surface hardness range for AISI 4140 material grade was 650 ± 50 HK. AISI 4140 shaft of diameter 14 mm will need a power density $\geq$ 21.5 Watts/mm^2 at 46 KHz to achieve effective surface hardening with optimum surface hardness range.

A family of curves was extrapolated from the experimental data and Master curve boundaries A and B were derived. Boundary B can be used to approximate the minimum power density requirement to achieve optimum surface hardness range 650 ± 50 HK for the treatment of AISI 4140 shaft. No hardening will take place with power density lower than boundary A.

Automated IGBT induction hardening is versatile for the case hardening of engineering components. With a sound knowledge of the system, parts varying from 0.2 Kg to 650.0 Kg with various geometrical shapes and sizes have been successfully case-hardened. Huge engineering parts known to suffer quench cracking under vacuum hardening conditions, may be effectively induction hardened to produce uniform case depths.

7.0 ACKNOWLEDGEMENT

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PROFILES

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