DESIGN AND CONSTRUCTION OF A SET-UP FOR INDUCTION HARDENING

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By

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ABSTRACTS

DESIGN AND CONSTRUCTION OF A SET-UP FOR INDUCTION HARDENING

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In this thesis, set-up for induction surface hardening is designed and constructed.

The set-up consists of an electronic circuit, a mechanical driver, and a plotter for temperature measurement with thermocouples. Electronic circuit is designed as to provide high frequency current. Mechanical drive is designed to hold the work piece properly in the work coil and also to feed the work-piece through the work coil to obtain through hardening. With the help of the thermocouples, the variation in the temperature of the work-piece is recorded with the plotter.

The experiments are performed to show whether the designed set-up is working properly and to see the effects of some of the parameters on the depth of hardening and on the heating time.

Key Words: Induction Hardening, Surface Hardening

ÖZET

İNDÜKSİYON AKIMI İLE YÜZEY SERTLEŞTİRME İÇİN DÜZENEK TASARIMI VE İMALATI

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Bu çalışmada indüksiyon ile yüzey sertleştime için bir düzenek tasarlandi ve imal edildi.

İmal edilen düzenek elektronik devre, mekanik sürücü, ve ısıl çift yardımı ile sıcaklık degişimini kaydeden bir çiziciden oluşmaktadır.Elektronik devre yüksek frekanslı akım elde etmek, mekanik sürücü ise iş parçasını bobinin içine yerleştirmek ve devamlı sertleştirme yapmak için tasarlandı. Çizici iş parçasının sıcaklık degişimini ısıl çift yardımı ile kaydetmekte kullanıldı.

Tasarlanan devrenin performansını ve bazı parametrelerin sertlik ve ısınma zamanına etkisini gözlemek için bazı deneyler yapılmıştır.

Anahtar Kelimeler: İndüksiyon ile Sertleştirme, Yüzey Sertleştirme.

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LIST OF SYMBOLS

a	Distance Between Work Coil and Work Piece
b	Distance Between Two Turns of Work Coil
B	Magnetic Flux Density
C	Capacitance of Capacitor
d	Depth of Penetration by Frequency
d_i	Inner Diameter of Work Coil
d_t	Depth of Penetration by Conduction Heat Transfer
D	Outer Diameter of Work Coil
D_R	Radius of the Work Coil
f	Frequency of the System
L_1	Inductance of Work Coil
L_2	Inductance of Tank Coil
N	Number of Turn of Coil
P	Power
r_1	Distance Between Source Point and Field Point
R, R_W	Resistance of Work Piece
V	Input Voltage
V_C	Voltage Across the Tank Capacitor
X_C	Impedance of Tank Coil
X_L	Impedance of Work Coil
W_R	Pitch of Work Coil
ρ	Resistivity
ϕ	Magnetic Flux
μ_o	Permeability

CHAPTER 1

INTRODUCTION

Most of the machine parts require a hard surface layer and a soft core, to resist impact loads, to have high wear resistance and to have high fatigue strength.

The treatment called case hardening, gives the steel a hard and wear resisting surface. By virtue of the core remaining comparatively soft and tough, the component as a whole shows high impact strength. Due to the development of compressive stresses in the surface layers during the case hardening treatment the fatigue strength of the steel is also increased.

Case hardening methods fall into two main categories. The first category consists of thermochemical treatments, so called because the surface chemistry of the steel is modified by the introduction of carbon and nitrogen and occasionally other elements. These processes are carburizing, nitriding and metallizing. The second category consists of selective surface-heating processes (local heat treatment). These processes are induction hardening, flame hardening, laser hardening, and electron beam hardening.

The methods in the first category need more time for completing the process like 10 hours. While in the methods of the second category, the hardening process can be completed in a very short time e.g. 10 seconds and these methods are practically applicable to any machine part.

Induction hardening among the others is aplicable to any complex shape part like gear. Short heating-up periods, minimum surface decarburization and oxidation are the advantages of this process. Easy processing on production line, low operating costs are other advantages of induction hardening. Induction hardening is done by inducing current in the work coil to the work-piece.

As alternating current flows through the work coil, a highly concentrated magnetic field is established within the coil. The magnetic field that established induces an electric potential in the part to be heated and since the part represents a closed circuit, the induced voltage causes the flow of current. The resistance of the part to the flow of the induced current cause heating by I^2R loses.

The pattern of heating obtained by induction is determined by the shape of the induction coil producing the magnetic field, the number of turns in the coil, the operating frequency, and the alternating current input power.

The rate of heating obtained within induction coils depends on the strength of the magnetic field to which the part is exposed. In the work-piece, this becomes a function of the induced currents and of the resistance to their flows. High-frequency current is generally used when shallow heating is desired; intermediate and low frequencies are used in applications requiring deeper heating.

Cooling rate influences the hardness of the parts. The interval between the end of heating and the start of cooling influences thickness of hard layer. Also, cooling method may be the cause of cracks on the heated part.

The aim of this study in the first place is to design and construct an induction hardening machine and second to perform a series of experiments to evaluate the effects of some parameters like frequency, heating time, power supply on the depth of hardening and on the hardness of medium carbon steel parts which are cylindrical in shape.

Previous works on induction heating and hardening are summarized in chapter 2. General review of surface hardening and induction heating is presented in Chapters

3 and 4. The construction of the apparatus and the experiments performed are explained in Chapter 5. The results are discussed in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

This chapter gives a brief survey of the most relevant literature related to the study reported in this thesis.

Section 2.2 is devoted to the developments made in induction heating machines. The factors which affect the hardness of the parts are discussed in section 2.3.

2.2. Development of Induction Hardening Machine

The development of machine construction and increase in specific loads and speeds of operation of machines and mechanisms presented the problem of developing methods of surface hardening for machine parts like crank-shaft journals.

In 1930's there were three alternative solutions of hardening problem. These were gas flame hardening, electroconduct hardening by Gevelings, N.V. method [1] and induction hardening developed by Vologding, V.P. and co-workers [2,3].

The electronical basis of induction heat treatment were developed in the first years of 1930. In most of the factories in Soviet Industries in the mid 1950's, as much as 30-40% of the machine parts requiring heat treatment were induction hardened.

Induction hardening method was used in the place of tempering in self tempering furnace [4]. However, the use of induction hardening was limited in those years to moderately loaded parts, which is explained by the fact that only the surface layer of the parts was hardened, and the "subsurface" retained the original properties, and also by the fact that most of the properties of steels subjected to induction hardening did not conform to induction hardening technique.

These shortcomings were eliminated with further development of induction hardening.

High frequency power supplies were summarized by Paschal, W.F. [5]. These are motor generator, AC/VDC/DC inverter, AC/VDC/DC inverter (reactor coupled),AC/AC inverter, and AC/DC/AC inverter (capacitor coupled).

Firstly, the motor generator has been the induction heating industry's high frequency workhorse since 1940's. During 1960's a number of inverter designs were introduced to the induction heating industry that involve some fundamental differences in power control.

The motor generator has a constant frequency and variable voltage output. Power rating of the motor generator is dependent on the output voltage and current (KVA) rating as shown in Figure 2.1.

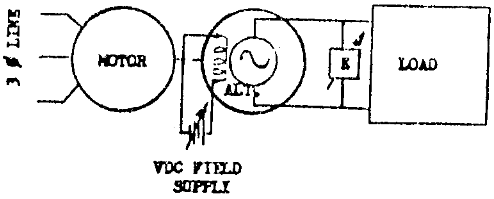


Figure 2.1 Motor Generator [5]

The AC/VDC/DC inverter, shown in Figure 2.2, has SCR control of the DC voltage, and the inverter frequency, although adjustment is tuned to represent a fixed frequency output essentially the same as a motor generator unit.

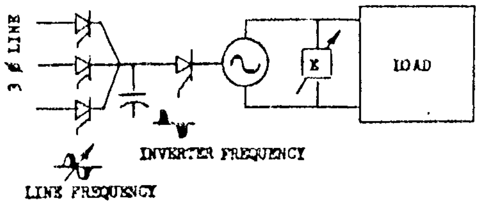


Figure 2.2 AC/VDC/DC Inverter [5]

The AC/VDC/AC inverter of Figure 2.3 is reactor coupled to the induction heating load and controls the firing rate of the inverter's SCR output current to increase or decrease power to the load in essentially the same way as the magnitude of a swinging pendulum controlled by synchronizing the applied power pulse with the resonant frequency of the pendulum.

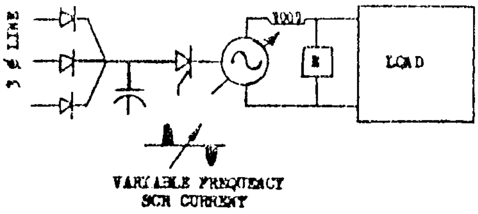


Figure 2.3 AC/VDC/DC Inverter (Reactor Coupled) [5]

The AC/AC inverter shown in Figure 2.4, has essentially a variable frequency characteristic. The frequency of the inverter circuit is dependent on the resonant frequency load condition, and power is controlled by the phase angle of the line SCR.

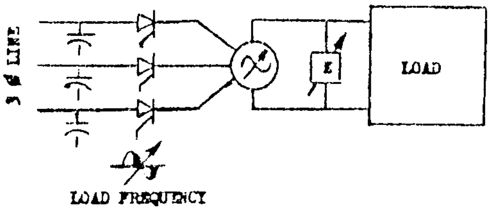


Figure 2.4 AC/AC Inverter [5]

The AC/DC/AC inverter shown in Figure 2.5 is capacitor coupled to the load similar to the reactor coupled inverter in Figure 2.3, with power controlled by the variable faring rate frequency of the inverter SCR current output. Again, the output voltage will vary with load conditions; however it is not a control parameter except in the case of voltage protection limits during operating power conditions.

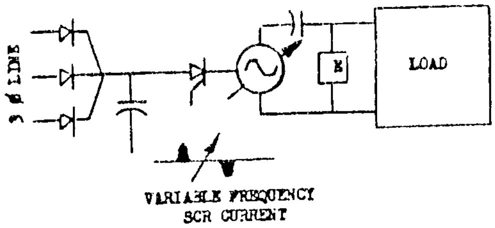


Figure 2.5 AC/DC/AC Inverter (Capacitor Coupled) [5]

2.3 Effects of Some Factors on Surface Hardening

The most difficult variable parameter to comprehend is the work-piece resistance, which is affected by two or three of the variable work-piece parameters, including resistivity, effective magnetic permeability, and load resonant frequency. Load resonant frequency is influenced from resonator which is constructed by the series connection of work coil and tank circuit. The capacitance of tank circuit was fixed, and inductance of work coil could be varied by changing work coil with different turn.

PASCHAL W.F., [5] said that one of the important parameter of the case depth is resistivity of the work piece. A relation of the resistance of the work piece and case depth is given by R [5].

$$R_v = \frac{\rho \pi N D}{d W_R} \tag{2.1}$$

$$d = 5040\sqrt{\frac{\rho}{\mu f}} \tag{2.2}$$

From Figure 2.6 it can be noted that when heating a steel from room temperature to 1093°C a change of resistivity in excess of five times will affect change in current penetration.

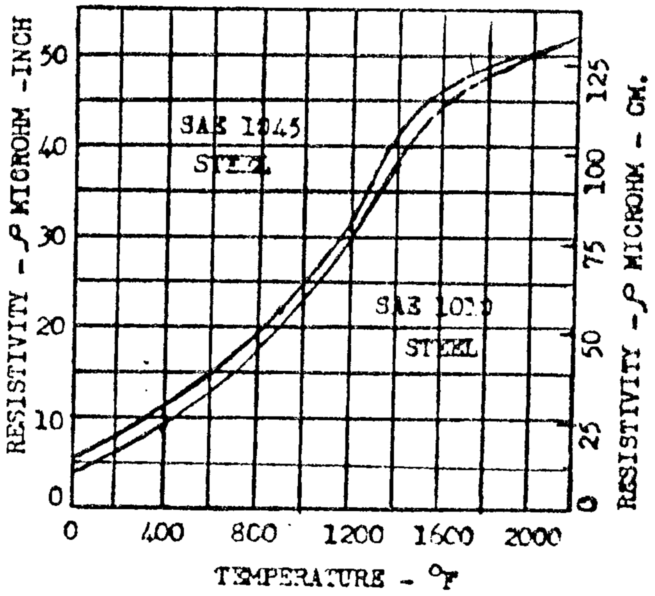


Figure 2.6 Resistivity of the Steel [5]

The permeability is also important parameter for induction hardening. In air (in the gap between the inductor and the work piece) the value of the permeability is $\mu=1$, the resistivity is $\rho=\infty$. The value of μ influence the current rate in the metal shown in Figure 2.7, whilst the displacement current, which is an infinitely small quantity in comparison with the conduction current and can be neglected in practice as suggested in reference [12].

The third important parameter is frequency, which is directly related to the work coil design. Inductance of work coil specifies the maximum current in the circuit and the resonant frequency. Coil design is also important for uniform heating of work piece. The design principles are discussed in reference[6].

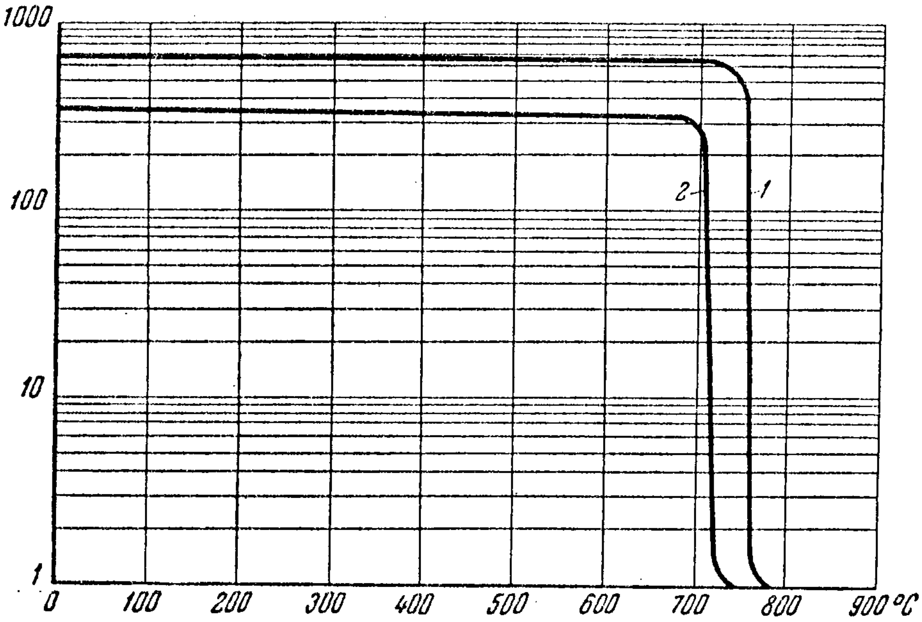


Figure 2.7 Variation in the Permeability of Pure Iron (1) and Euetectoid Carbon Steel (2) When Heated From 0 to 900°C [6]

In metals handbooks [6] some restrictions on the dimensions of coil are suggested. For the work coil, copper tubing may be used, and it must be wound at least 3 mm. in diameter, but for unit of power 20 to 50 KW, it is usually 5 mm or 2 mm apart with a 5 to 3 mm space between the work piece and coil.

Baranov, V.S., Kosmovich, L.S.,and Parnas, A.L., [7] discussed that some problems may arise during and after induction heating and hardening. They are non uniform heating, the formation of crack, and significant deformation. They suggested that above problems can be eliminated by a proper coil design and a correct method for quenching. The coil must be designed in such a way that the part is heated by a multiturn cylindrical inductor with turns located at an angle of 17-25° in relative to a plane normal to the axis of the part. For quenching, they have suggested that quenching must be done with water from a sprayer located after the inductor which is quenched only a portion of the circumference of the the part. The quantity of water supplied to the sprayer is measured by load type flow meters.

The other important factor is cooling of the heated part. Vigorous cooling by water shower first come into use as early as the initial stages of the development of induction of surface hardening [12]. Cooling by a rapidly moving stream of water was subsequently developed [8].

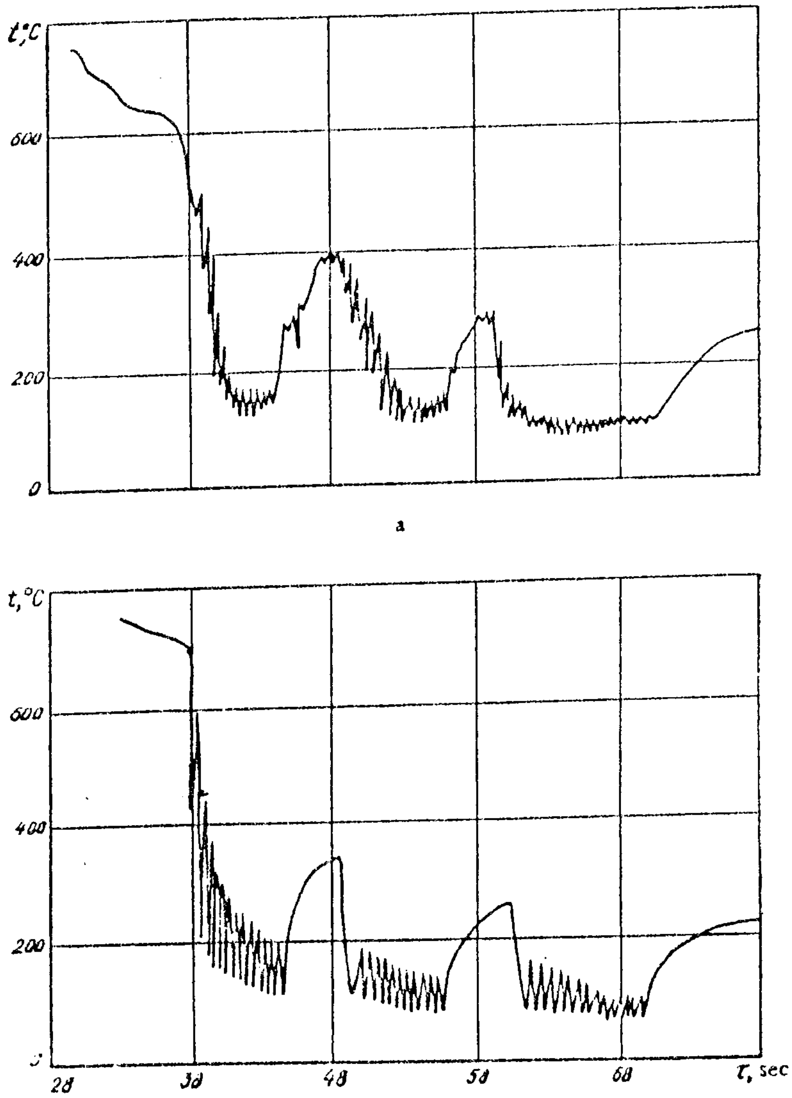
Using of rapid organized cooling that can be controlled over time is one of the significant advance in the modern technology of electrothermal treatment.

Shepelyakovskii, K.Z. [9] mentioned that this cooling is characterized not only by the simplicity in which it is carried out and its economy but also makes it possible to obtain a set of improved properties for the hardened steel and to prevent the formation of cracks during hardening.

Bagatyrev, Yu.M., Shkylyarov, I.N, and Shepelyakovskii, K.Z., [10] said that cooling during hardening should be intense and uniform; this reduce thermal stresses during hardening and prevents the appearance of cracks.

Baranov, V.C., Kosmovich,L.S., and Parnas, A.L., [7] had made the theoretical analysis of the heating and quenching processes, based on a computer numerical solution of the thermal conductivity and thermoplasticity. Measured and calculated temperature curves of the quenched part are same as shown in Figure 2.8.

The method of calculation was similar to that measured given in [13], in which the hardening process of plates was investigated. The temperature fields in the cross section of the half-axle were calculated using an axially symmetric unidimensional method. A comparison of the values obtained with calculations using a two dimensional method showed that with the unidimensional calculations an acceptable accuracy is obtained with a significant decrease in computer time.



a

b

Figure 2.8 Temperature of the Half-Axle Surface During Quenching a) Measured b) Calculated [13]

The quantity of heat generated in the metal, the magnetic permeability, and effective depth of penetration of the current into the part were determined during numerical calculation by the iteration method. As shown in Figure 2.9 at the start of heating the depth of penetration of the current was shallow (less than 1 mm) but after a rapid increase of the surface temperature beyond the curie point, depth of penetration does reach to 8 mm at the end of the heating.

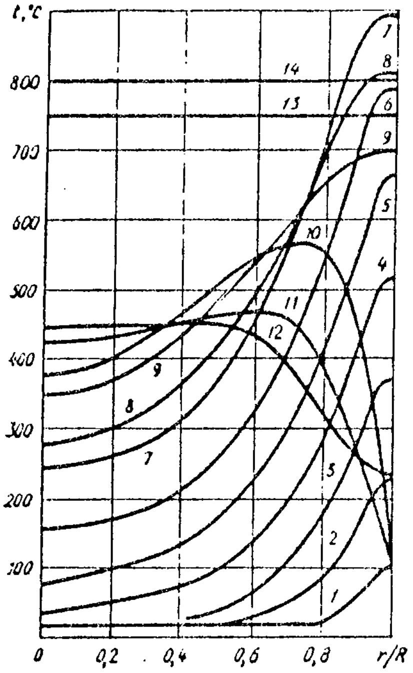


Figure 2.9 Temperature Distribution Across the Half-Axle Cross Section: 1) 0.5 sec After the Start of Heating; 2) 2.0 sec After; 3) 4.5 sec; 4) 8.1 sec; 5) 12.6 sec; 6) 18.2 sec; 7) 24.8 sec; 8) After Partial Cooling to 27.2 sec; 9) 35.1 sec; 10) After Water Quenching to 38.0 sec; 11) to 42.0 sec; 12) After Air Cooling to 46.0 sec; 13) Curie Point; 14) Hardening Temperature

All steels are not used for induction hardening. Best results are obtained from medium carbon steels, like 1035-1064 and some alloy steels such as, H13, HNV23 [11,14].

CHAPTER 3

SURFACE HARDENING

3.1 Introduction

Many types of heat treatment processes are used to modify the surface properties of mechanical components. It is the aim of this chapter to compare them, since selection of the particular process to be used is among the initial considerations of design engineer.

3.2 General Review of the Processes Available

There are number of heat treatment processes that are used to produce harder, and more wear, and fatigue resistant surface on steel parts. These processes are used mainly for engineering components and have the attraction that they result in a material having different properties in core and case. The core is normally treated to be considerably more ductile and tougher than the surface.

These surface treatments fall into two main categories. The first category consists of thermochemical treatments. Thermochemical processes may be subdivided into the following main types: (1)

carburizing and carbonitriding; (2) nitriding; (3) ferritic nitrocarburizing; and (4) metallizing. The second category consists of selective surface hardening processes, where only the surface is hardened and the core remains in its pretreated conditions. These processes are subdivided into: (1) induction hardening; (2) flame hardening; (3) laser hardening; and (4) electron beam hardening.

There are many variations both major and minor of these basic processes. The large number of processes arise not so much as a result of the demands of engineers to produce variations to meet their exact service requirements, but because of the large number of alternative competitive approaches that can be used for processing to achieve similar but not identical, end results.

The features of these processes of most importance to the engineer are:

1) Processing temperature, since this affects distortion;

2) Mechanical properties of the case, in particular surface hardness;

3) Case depth;

Since distortion is affected mainly by the processing temperature used for surface hardening, process temperature and the factors affecting its selection are considered in some details. It should be noted that steel composition in itself has little effect on distortion, but it does influence the quenching medium used, which can have a significant effect on distortion.

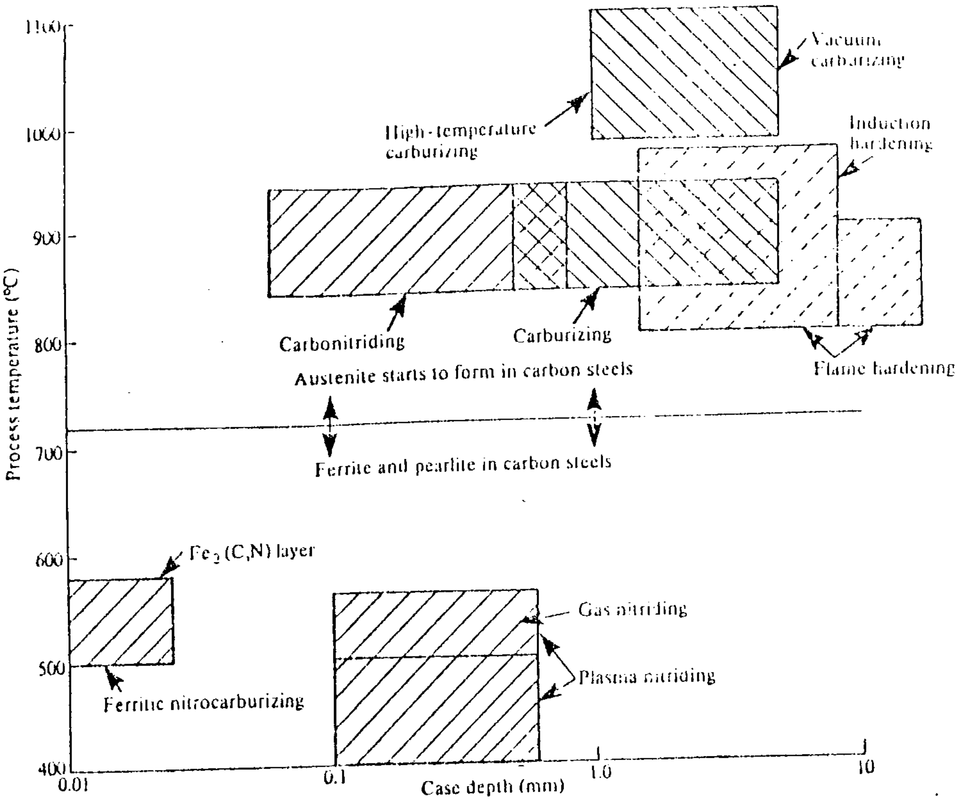


Figure 3.1 Comparison of Process Temperature and Case Depth Produced by the Various Surface Heat Treatment [15].

3.3 Processing Temperature.

In Figure 3.1 the surface heat treatments are compared schematically in terms of the process temperature and typical range of case depths produced.

The engineer is concerned with process temperature mainly because distortion is directly related to the temperature. There are two basic types of process: (1) those carried out at low temperature, namely less than 600°C when the steel is in the ferritic state and (2) those carried out above 800°C when the steel is in the austenitic state.

The ferritic state is the stable form of carbon and low-alloy steels below about 723°C. If carbon steel is heated above 723°C, the stable condition of steel at high temperatures, known as austenite, begins to form. As the temperature is raised, increasing amount of austenite are produced until 800°C, at which the whole structure is austenitic (for 0.4 percent carbon steel) . This is illustrated by the iron-carbon equilibrium diagram in Figure 3.2.

If the cooling rate after austenizing is low, the structure will be a mixture of the relatively soft phases ferrite and pearlite as shown in equilibrium diagram. Fast cooling rates of 200-300 °C/s, which are typical for oil quenching of small sections, will, however, cause the austenite to transform to martensite, the hard phase commonly found in quenched steels. The effects of cooling rate and carbon content on the hardness and structures produced in carbon steels are shown in Figure 3.3

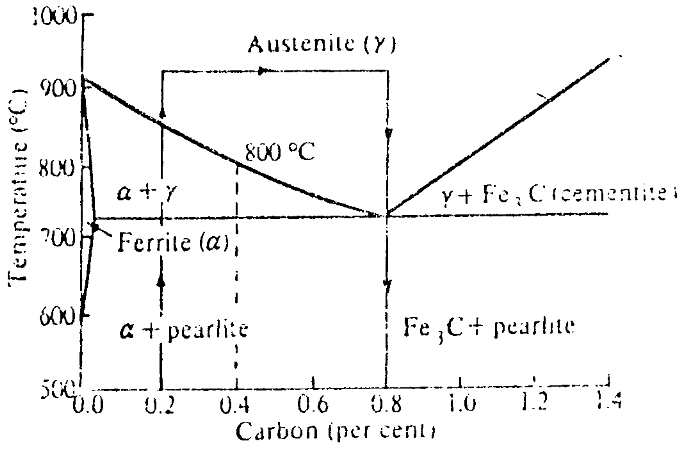


Figure 3.2 Iron Carbon Equilibrium Diagram Showing Progress in Carburizing the Outer Layer of a Component [15].

If a low temperature process is carried out (below 700°C) no ferrite-austenite phase change occurs, thus large dimensional changes are avoided and the need for further grinding operations to achieve specified dimensions is reduced.

Nitriding is carried out on components already in hardened and tempered condition. However, since thermochemical processes rely on the diffusion into the steel of carbon and nitrogen and since diffusion rates increase exponentially with temperature, at low temperature processes take much longer times and produce shell over case depths. Nitriding and the ferritic nitrocarburizing processes are carried out, normally between 500-580°C in the ferritic range. Case depths are always less than 0.5 mm. Higher temperatures of nitriding which could produce greater case depths in reasonable times (say less than 90 hr) are not practical [15]. Distortion is very slight in nitriding.

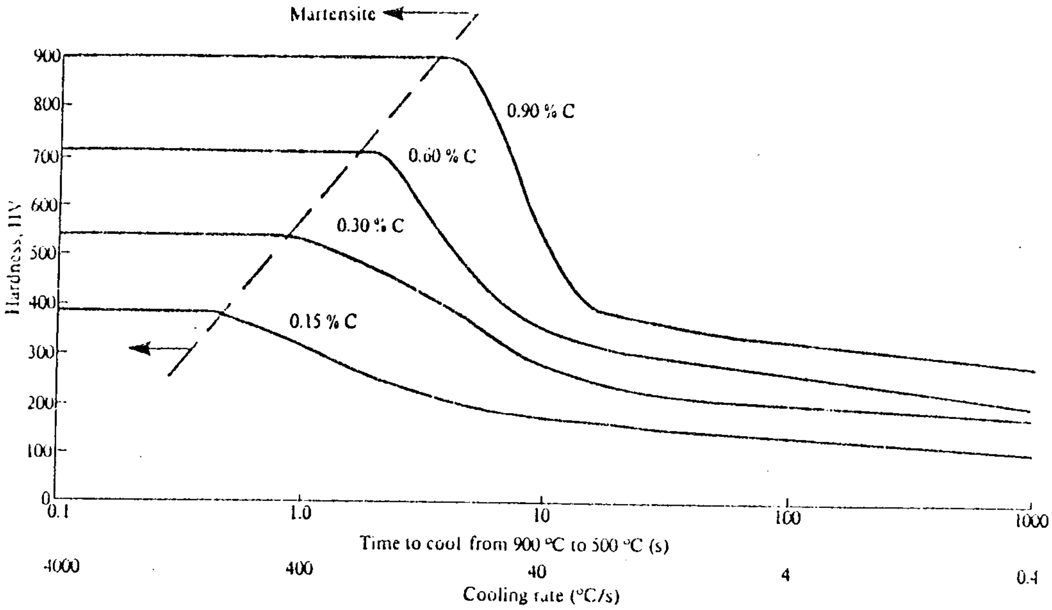


Figure 3.3 Effects of Cooling Rates on Hardness of Different Carbon Content [15].

Carburizing is carried out on material in the austenitic state at temperatures of 850°C or above, and much greater case depths (several millimeters) can be achieved in relatively short processing times of less than 24 h. Quenching to harden the component results inevitable dimensional changes and the risk of distortion. Further grinding to achieve desired dimensional accuracy may be required.

Localized heating to the austenitic state by induction or flame hardening is likely to result in much less movement or distortion since the bulk of the component remains uneffected.

3.4 Properties of the Case

Surface heat treatment may be used to improve two main properties of the surface; (1) fatigue strength, (2) wear resistance. It is rarely possible however to optimize all of these properties with one type of heat treatment.

3.4.1 Fatigue Strength

With all surface heat treatments, the fatigue strength may be affected in two ways. Firstly, the material of the case may, because of its different composition and structure resulting from the surface heat treatment, develop a higher fatigue strength than that of the core. Secondly, surface residual stresses may be developed which affect the fatigue behavior. The development of compressive surface residual stress will increase the fatigue life in such a situation [15].

Considering the first effect, the fatigue strength of the case is increased above that of the core by various mechanisms depending on the process. With carburizing the increase in carbon in the case raises the hardness, the tensile strength, and initially, the fatigue strength. The general relationships between carbon and these mechanical properties are shown in Figure 3.4. Excess carbon must be avoided,otherwise embrittlement or lower hardnesses and retained austenite will occur. The core, which typically contains 0.14-0.2 percent carbon, will have a lower level of these properties.

With nitriding a very hard layer of alloy nitrides are formed. Since the solubility of nitrogen in liquid steel is limited at a level much below that in the nitrided layer it is not possible to melt, cast, or forge alloys of comparable composition and structure in order to show the effect of nitrogen on these three mechanical properties.

Localized surface heat treatments are carried out on material that is the fully annealed, normalized, or hardened and tempered condition. After austenizing by local heating the surface is water quenched and develops higher hardness and mechanical properties because of the higher cooling rate of the quenches compared with that when pretreatment is by annealing or normalizing. If the component is pre-hardened and tempered, a higher tempering temperature will normally be used for the core that giving a higher case hardness.

The second way in which fatigue strength is affected by the surface heat treatment must now be considered. Generation of compressive surface residual stresses has a favorable affect on fatigue strength. Here too the mechanism of development of residual stresses depends on the process.

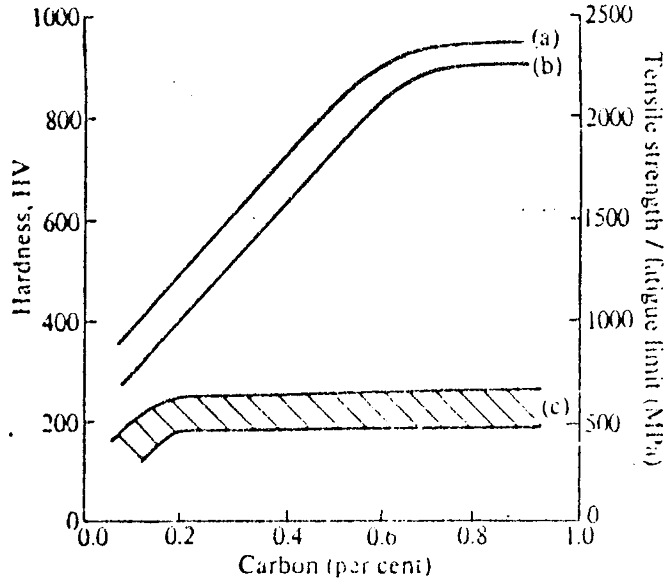


Fig. 3.4 Effect of Carbon Content on (a) Tensile Strength, (b) Hardness, and (c) Fatigue Limit of Quenched and Tempered Steel [15].

Local surface hardening must now be considered. When the surface layers are heated to the hardening temperature of about 850°C they expand and are restrained by the cold core. As this temperature is very high in relation to the creep behavior of a low alloy steel, the surface layers accommodate plastically to the core. On quenching, the surface layers contract on cooling and then expand when the martensitic phase is formed from austenite. Residual tensile stresses of considerable magnitude are likely to occur at the case-core interface.

The developments of compressive residual stresses in carburized cases are more complicated and under certain circumstances may not occur. After carburizing at the process temperature the surface layers are stress-free, any growth caused by carbon pick-up being accommodated by plastic straining. The effect of carbon is to lower the martensitic transformation temperature. Consequently, as the carburized component is quenched, provided the temperature profiles in the specimen are appropriate, sequential transformations from the core to the surface of the case occur.

A number of factors can however, prevent this sequential transformations from center to outside and lead either lower compressive stresses at the surface, or even tension stresses. Together with compressive stress, the hardenability of the steel and the quench severity are important factors in effecting the sequence of transformations. The use of lower carbon steels will also assist the preferred squence of transformation.

Residual compressive stresses up to 400 N/mm^2 are quoted for carburized steels, directly quenched with no subsequent tempering [5]. In general, the highest residual stresses are developed with steels of lower core hardness. Increasing the case depth, increases the depth of the compressively stressed layer and consequently, in this section particularly, the residual tensile stress in the core. Tempering even at moderately low temperature of 150°C can halve the residual stress. Refrigeration and the consequent transformation of any retained austenite is found to have little effect on the residual stress.

It should be emphasized however that one of the main attributes of surface heat treatments, particularly nitriding, is to counteract the adverse effect of notches, changes of section, rough surface finish etc. on the fatigue properties of a component. The austenitic processes that are followed by quenching to harder, demand, as in all hardening operations, that geometric factors causing stress concentrations be minimized to avoid quench cracking caused by thermal stresses. In the case of carburizing and local surface hardening the carbon content at the surface is likely to be greater than 0.4 per cent, but the danger of quench cracking during the pre-hardening treatment can be minimized in nitriding steels by using lower-carbon steels.

3.4.2 Wear Resistance

At least as far as abrasive wear is concerned there is a marked correlation of wear resistance with hardness value and hence carbon content. The maximum hardness that can be developed with carburized steels occurs at about 0.8 per cent carbon, as above this level in most steels soft austenite is retained on quenching and does not transform to martensite.

Local hardening produces lower hardnesses in the case than does carburizing. This is because of the carbon content of the steels used, but from the point of view of component life, the lower wear resistance may be balanced by the greater depths of hardening that can be achieved. It is not normally considered practical to use higher carbon steels because of the low toughness and the increased susceptibility to quench cracking that would result.

The nitriding steels produce much higher surface hardnesses but the depth of case produced is limited to less than 0.6 mm, a higher value that can normally be tolerated for wear. Maximum hardness and wear resistance are achieved by the metallizing processes which produce very hard compounds, such as iron-boride and titanium-carbide

3.5 Case Depth

One of the most important variable in any of the heat treatment process is case depth. If wear resistance is the objective and the wear rate is known or determined, then the case depth for a given life is easily calculated.

If, however, the objective is improved fatigue resistance then the required case depths should be greater in size. The case depth required will also be influenced by the fatigue limit of the case.

3.6 Core Properties

The strength of the core is an important factor in avoiding case crushing. This phenomenon is commonly found with improperly designed gears and is attributed to sub-surface fatigue failure in shear. It is more likely to occur with inadequate case depths and inadequate case or core hardenability.

3.7 Comparison of Surface Heat Treatments

Carburizing is most widely used process and is generally the cheapest approach to high-performance components requiring a high level of mechanical properties throughout the core and case. It may be regarded as a useful standard against which other processes may be compared.

If the core properties of mild steel are adequate for the design but improved wear fatigue resistance is required, carbonitriding, a variant of carburizing that increases the hardenability of the case by introducing nitrogen, is recommended. this process is cheap or cheaper than carburizing and growing in popularity for lower-duty components.

Where design stresses are low for both the core and case, ferritic nitrocarburizing should be used. This is the shortest, and hence generally the cheapest, surface heat treatment and its use for improving the fatigue, and wear properties of mild steel is widespread. The limitation of this process is the very thin iron nitrided case.

Where the highest fatigue strength is required in the process of stress concentration such as at a notch, key-hole or sharp radius, nitriding should be selected. Such designs are often non-suitable for carburizing because the stress-concentration element of the design may lead to high-carbon martensite cracking on quenching.

Where localized or selective hardening is required, induction or flame hardening will generally be found to be the most economic approach particularly if the component is symmetrical and coil design and manufacture are simplified. If accessibility of the surface to be hardened is difficult, or if distortion occurs with induction or flame hardening, then laser or electron-beam hardening should be considered.

The deciding factor should always be the overall cost, about which generalization cannot be made. Space considerations will frequently determine whether a low-strength component can be used or whether another more costly, more compact high-duty component is selected. Equally important are finishing costs, which in connection with gears can lead to an economic decision in favor of the more expensive nitriding steels in order to avoid distortion and expensive machining time on finishing.

The designer should also be aware of the general effect of heat treatment processes on surface finish. The higher the processing temperature and the longer the time, the greater will be the determination of the good surface finish. Rough finishes can actually be improved with heat treatment, and is more frequently found with salt-bath process.

CHAPTER 4.

INDUCTION HEATING

4.1 Introduction

This chapter is devoted to the explanation of the basic principles of induction heating. The design of work coils, resonant frequency, power requirement, and characteristics of the circuit are discussed in separate sections.

4.2 Fundamentals of Induction Heating

When an electric current passes through a conductor, an electro-magnetic field is created round it. If the conductor is a coil, a magnetic field flows through the coil. This field persists even if a metal bar is inserted into the coil, as shown in Figure 4.1. If the magnetic flux is created by a high frequency alternating current, it gives rise to eddy current on the surface of the metal bar as shown in Figure 4.2, which consequently heats the part. In iron, hysteresis losses also contribute to some extent to the temperature rise up to curie point (700°C), above which iron is non-magnetic.

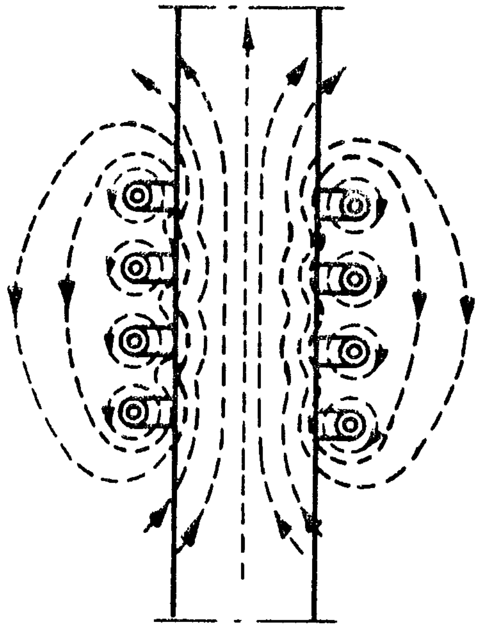


Figure 4.1 Path of Magnetic Flux Through a Metal bar Inserted in a Coil Through which an Electric Current is Flowing

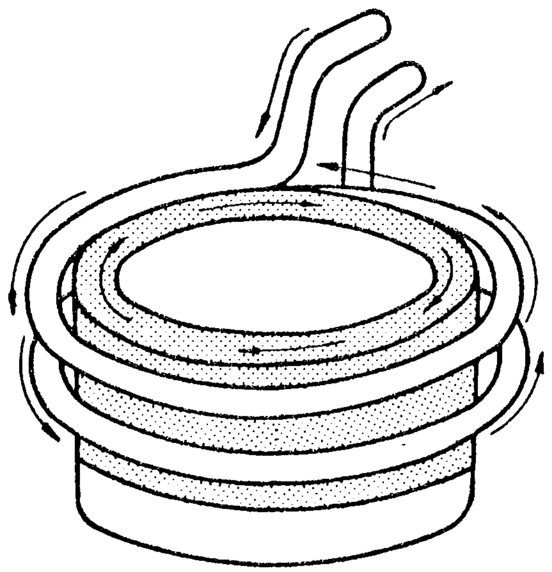


Figure 4.2 Path of the Electric Current in the Coil and Metal Bar During Induction Heating

The depth of the penetration of the heat is governed mainly by the power and frequency employed. Usually power input is between 0.1-2 kw/cm^2 of the heated surface. As suggested by Thelning, K.E. [17], the relationship between depth of penetration and frequency can be represented approximately by using the following simplified expressions, which are valid for the temperature rise in steel up to the hardening temperature.

$$d=\frac{2}{\sqrt{f}} \qquad \text{cold state } (20^{\circ}C) \tag{4.1}$$

Where, d is depth of penetration in (mm) and f is frequency in cycles per second (Hz). Owing to heat conduction in the material during heating, the overall depth of penetration is large. It is possible to calculate the additional penetration due to heat conduction from the following expression.

$$d_t=0.2*\sqrt{t} \tag{4.2}$$

Where d_t is depth of additional penetration in mm, t is time in second. The total depth of penetration is obviously $d+d_t$. It should be emphasized that these expressions give only a rough estimate of the depth of penetration and they have been included here only to show the fundamental effects of frequency and time.

4.3 Design of Work Coil

The success of induction heating applications is related to the selection and design of the proper work coil. The design involves the determination of the shape and size of the work coil. The governing factors which must be taken into account in the design of work coils are the shape (or configuration), size of the part, and the frequency.

Parts with different configuration require different work coils. As an example, consider a gear for induction hardening. Hardening area of the gear tooth is the working surface. Cylindrical work coil is not successful for gear treatments. The coil that is shown in Figure 4.3 must be used.

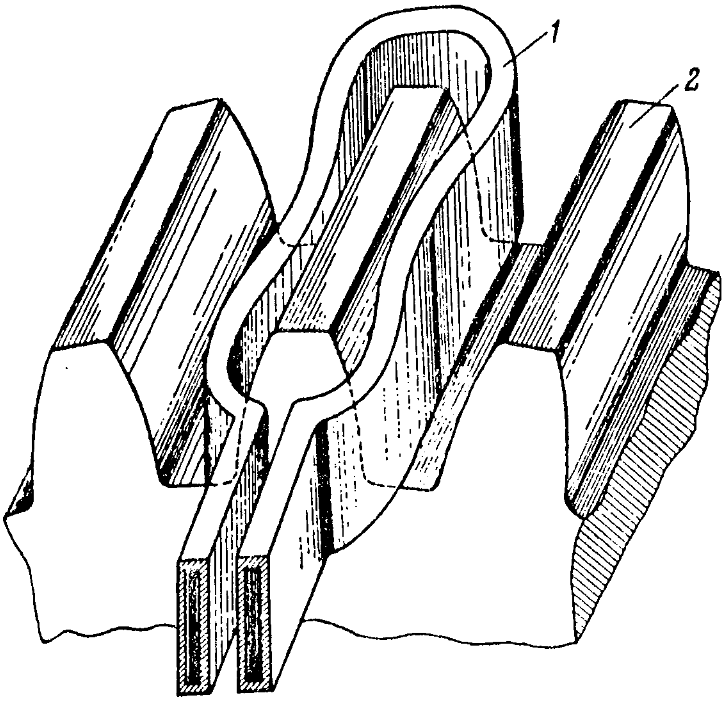


Figure 4.3 Diagram Showing the Relative Position of the inductor and the Tooth of Gear [12].

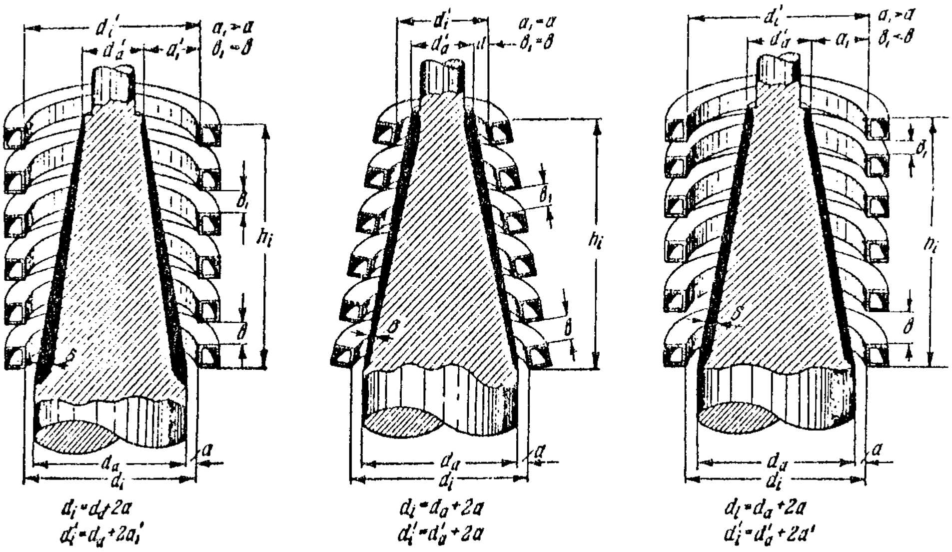


Figure 4.4 Coils for Hardening of Tapered Shafts [12].

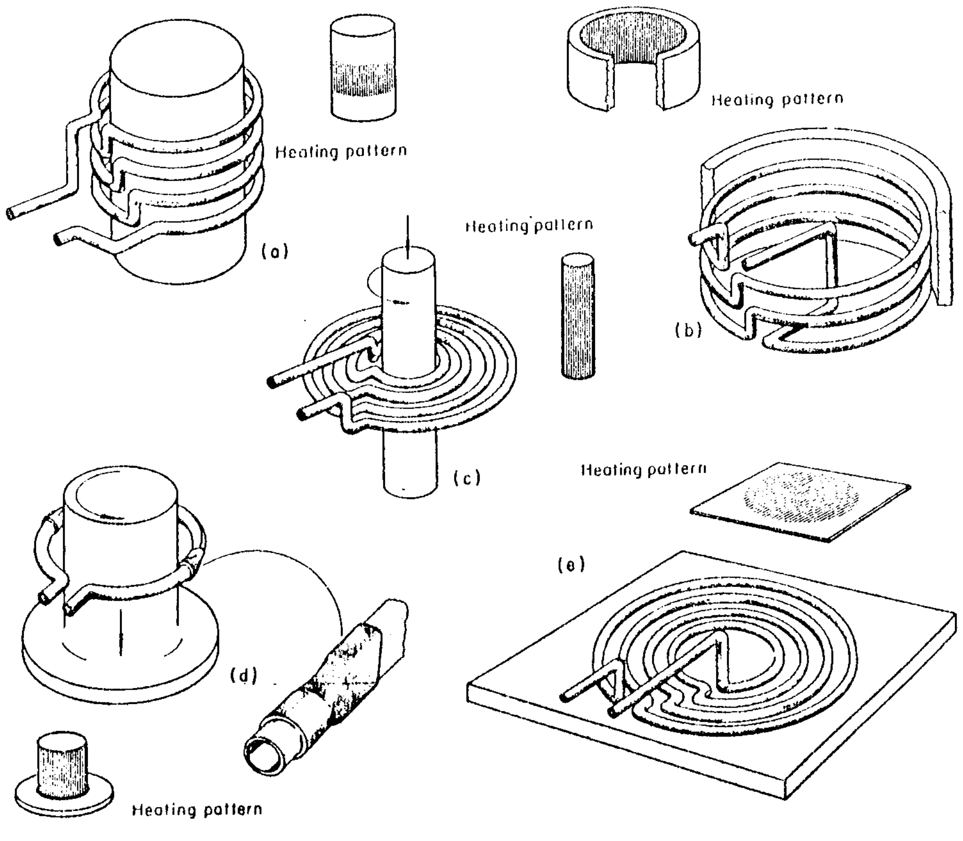


Figure 4.5 Typical Work Coil for High Frequency Units Some Other Work Coils and Their Heating

For tapered surface, effect of coil shape to the penetration of the hardness along the lengths of the parts are illustrated in Figure 4.4.

Some other work coils and their heating patterns are given in Figure 4.5.

The main factors affecting the choice of work coil shapes are the following:

a) The frequency of supply current which determines the depth of current penetration into the material being heated.

b) The magnitude of the power density ΔP brought to each square centimetre of the surface to be heated on. The values of ΔP affects the temperature distribution over the cross-section and along the surface of the zone to be heated.

c) The shape and thickness of the sections to be heated, and their position on the work-pieces ; these factors determine the accessibility and the convenience with inductor can be placed in position (heating external or internal zones, slots, and similar items).

Beside these main factors; there are other parameters which influence the design of coil like distance between work-piece and work coil and distance between two turns, as illustrated in Figure 4.6.

The air gap between the part to be heated and the work coil does not normally exceed 2-5 mm [13]. Increasing this gap causes a sharp drop in heating efficiency and decreasing it considerably complicates location of the work piece in the haeting zone and the increasing possibility of electric flashover in the gap between the inductor and the work piece.

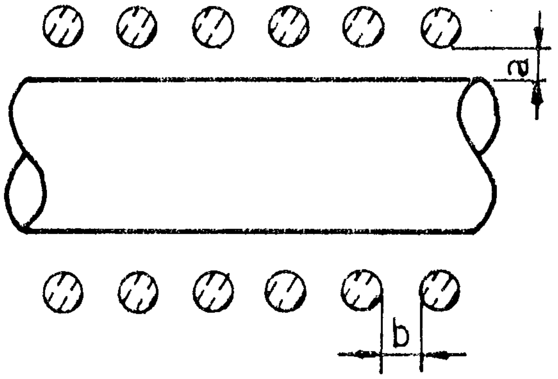
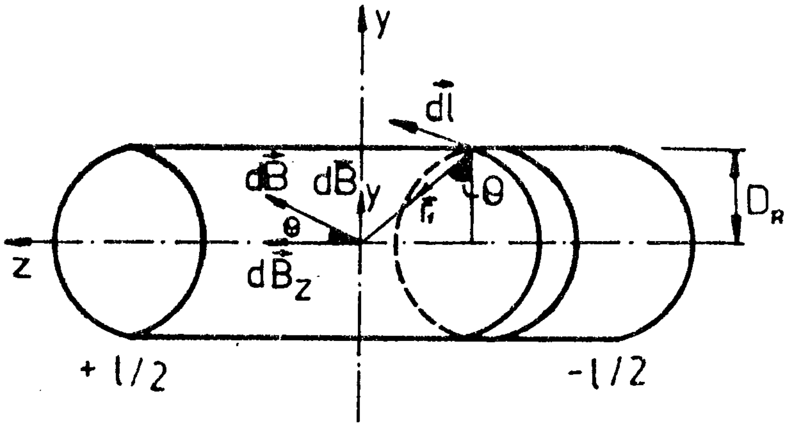


Figure 4.6 Relative Position of Inductor and Work Piece

Lozinskii, M.G. [12] also suggests that the coils are usual wound with a distance of 2-5 mm between turns. By varying this distance it is possible to influence the rate of heating to a very large extent.

Commercial copper tubing may be used for the coils. Its temperature increases by radiation from work piece temperature. So the tubing must be large enough to permit an adequate flow of water for cooling.

For rapid heating of the work piece maximum power must be available. Power converted to heat is $P=I^2R$, here is changing with the temperature of the heated part but not much, so maximum current must be obtained for maximum power. The current becomes maximum when impedances of tank capacitor and work coil are equal. All the design parameters may be selected relative to the inductance of the work coil. The critical calculation procedure for the inductance of the work coil for a solenoid shown in Figure 4.7, is given below.



Fgure 4.7 Solenoid for Cylindrical Coil

Firstly magnetic flux density is calculated from Biot Savart's Law [18].

$$d\vec{B} = \frac{\mu_0 I_0}{4\pi} * \frac{\vec{dl} x \vec{r}_1}{r^2} \qquad (4.3)$$

Where $\vec{dl}$ is a vector at the source point tangent to the conductor and $\vec{r}_1$ is the vector directed from the source point to the field point. Our field point is at source point to the field point. Our field point is at the origin point of coordinate system, and r is the distance from the source point to the field point.

The vector, $\vec{dB}$ is pointed perpendicular to the plane formed by the vectors $\vec{dl}$ and $\vec{r_1}$. If line integral along one loop is taken, y-components oriented in opposite directions will cancel each other based on the assumption that magnetic flux density B is constant across the crossectional area and along the solenoid. Hence, z components exist only. Equation 4.3 can now be rewritten as:

$$dB_z = \frac{\mu_o I_o}{4\pi} * \frac{dl}{r} \cos\theta \qquad (4.4)$$

$$r = \sqrt{D_R^2 + Z^2}$$

$$\cos\theta = \frac{D_R}{r}$$

Above equations are valid for only single wire. Now assuming that wire is also wound, the current on d_z strip can be written as

$$I_o' = \int_{-\ell/2}^{\ell/2} \frac{NI_o}{l} dz \qquad (4.5)$$

Substituting equation 4.5 into equation 4.4, the differential magnetic induction arises from I_O', can be obtained as follows

$$B_z' = \int_{-\ell/2}^{\ell/2} \frac{\mu_o I_o R^2}{2\ 1(D_R^2+Z^2)^{3/2}}\, dz \qquad (4.6)$$

or

$$Bz' = \frac{\mu_o I_o N}{\sqrt{4D_R^2+1^2}}$$

The magnetic flux in the solenoid is then determined as,

$$\phi = B_z' A \qquad (4.7)$$

Where, A is crossectional area of coil and it is (π R^2). The inductance interms of number of turns, magnetic flux dencity and current is expressed as;

$$L = \frac{N\phi}{I} \qquad (4.8)$$

Then, the inductance of the coil can be determined by substituting the expression for L, and equation 4.7 into equation 4.8 as

$$L = \frac{\mu_o N^2 \pi D_R^2}{\sqrt{4D_R^2+1^2}} \qquad (4.9)$$

As noticed in equation 4.9, the inductance of the coil has come out to be the function of μ_o, number of turns, radius of the coil and the length of the coil. The adjustments of so many parameters is the difficulty arises in the design study of the work coils.

4.4 Frequency Generator

Induction hardening is generally done at frequencies of 1000 Hz or higher. The types of low frequency and high frequency equipment commercially available are discussed below.

4.4.1 Static Frequency Converter

Although there are several types of static frequency converters, the most common is the frequency tripler. Basically tripler consists of an iron core transformer with three sets of windings , one for each input phase. Each phase voltage is applied to its own reactor and to the load in series operation of the tripler is based on the summation of pulses, a 50 cycle suply current is increased to 180 cycles.

A static frequency converter of the type described provides a highly efficient means for through heating steel bars of a given diameter, depending on output frequency.

4.4.2 Motor Generator Units

Motor generator units consist of a high frequency generator driven by a motor. Induction motors, which may be mounted integrally with the generator or separately on a common base are used with 1, 3 and 10 kc generators.

4.4.3 Vacuum Tube Units

Electronic tube units consist of a power supply section and an oscillator section. The power section provides the high voltage for the oscillator tube after rectification to a pulsating direct current usually by mercury vapor tubes. The oscillator tube and tank circuit for consisting of a matched inductor coil and capacitor comprise the oscillator section. The oscillator tube controls the amount of electrical energy delivered to the tank circuit from which the energy is removed by the inductance with the coupled load. The frequency developed in the converter is determined by the inductance of the tank coil and capacitor which from a parallel tuned circuit. A load matching network electrically coupled to the tank circuit is used to transmit tank circuit energy to the work.

4.4.4 Spark Gap Units

Spark gap units consist of an electrical circuit that alternately charges and discharges a capacitor by means of a spark gap arrangement. The 25, 50, or 60 cycles supply voltage is increased to several thousand volts by an input transformer. The secondary terminals of the transformer are connected to a capacitor through coke coils constructed to allow passage of low frequency current but to restrict the flow of high-frequency current set up by the discharge of the capacitor. The spark-gap arrangement acts as a valve that permits the capacitor to discharge periodically the work coil and or inductor connected in series with the spark gaps to complete a circuit for the discharge of the capacitor. The frequency, fixed by the inductance and capacitance value in the discharge circuit is in the range of 20000 to 60000 cycles.

The frequency generator, used in this work is explained in the following section.

4.5 Oscillation Principle of Single SCR

The frequency generator designed in this thesis consists of a tank circuit which is controlled by a single SCR as shown in Figure 4.8.

A single SCR is used, thus minimizing the cost of the semiconductors and associated triggering circuit. The voltage across the SCR and other components is reasonably constant from no load to full load thus minimizing component voltage rating.

The term oscillatory circuit is used for devices consisting of capacitance C and inductance L, and also possessing a certain pure resistance R. Owing to the energy dissipating effect, this pure resistance is not considered in this study. If capacitor with a capacitance C is charged to a voltage V, the energy stored in it will be $CV^2/2$. This energy transfers to the inductance L and returns to again to the capacitor C; further more, the speed of this energy oscillation process (frequency of the oscillation) depends on the values of L and C. Because a certain amount of energy will be dissipated in internal resistance of circuit elements after each cycle of oscillation the stored energy in the capacitor will be reduced and the oscillation will die out if it's not controlled. So as illustrated in Figure 4.8 the oscillator is by controlled diode and thyristor combination.

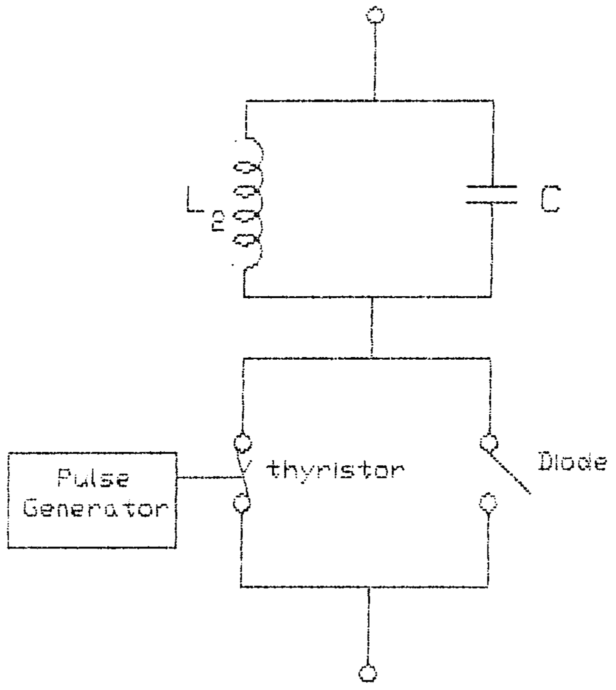


Figure 4.8 Oscillator and Control Unit

The diode is used for rectification purpose and its operating principle is explained in Figure 4.9. For the region defined by 0 to π of the sinisoidal input voltage, the polarity of the voltage drop across the diode would be such that the short-circuit representation would result and the circuit would appear as shown in Figure 4.9a. For the region π to 2π the open-circuit representation would be applicable and circuit would appear as shown in Figure 4.9b. The complete resultant output waveform is as shown in Figure 4.9c for a sinisoidal input.

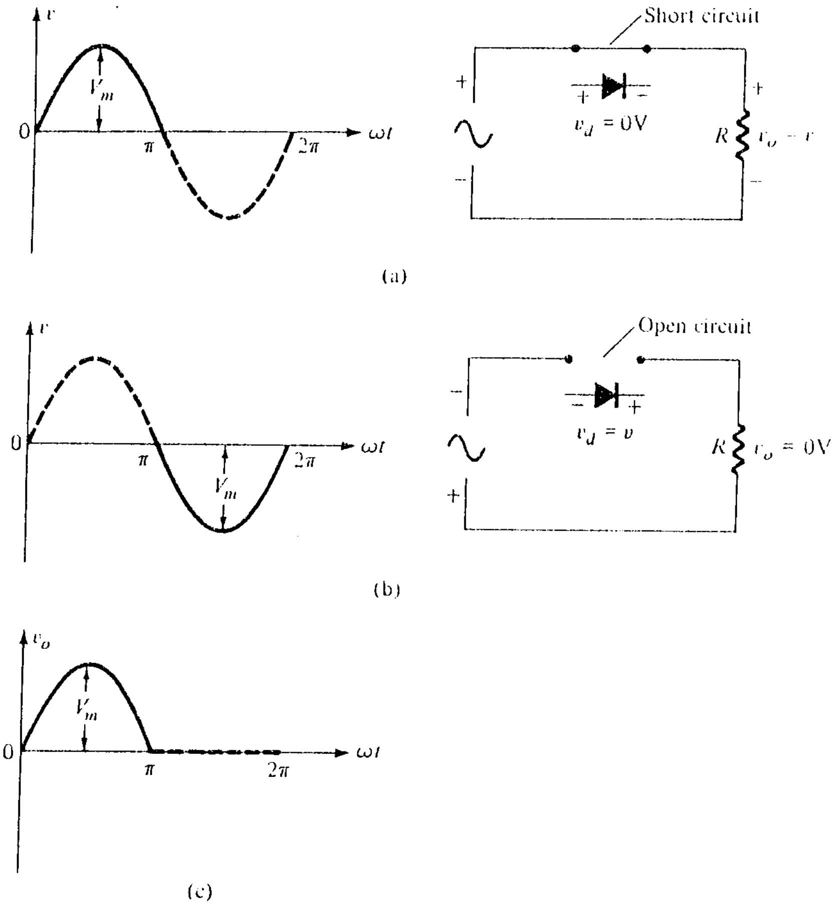


Figure 4.9 Rectifying Action of the Diode

Thyristor is three terminal switch consisting gate, anode, and cathode. It is turned on by forcing a small current (milliampere) into its gate. Given a sufficient anode current (milliampere) the thyristor latches into its conducting state and stays latched even after the gate current is removed. During the turn on interval, the anode-to-cathode voltage falls from it blocking level to its conducting level of about a volt. To turn off the thyristor, the anode current is reduced below its holding level by external means. It will remain in this off state provided that its anode voltage remains during the required turn-off time. If gate is triggered at 180°, thyristor is just similar to diode. When it is triggered below 180° wave is shown in Figure 4.10

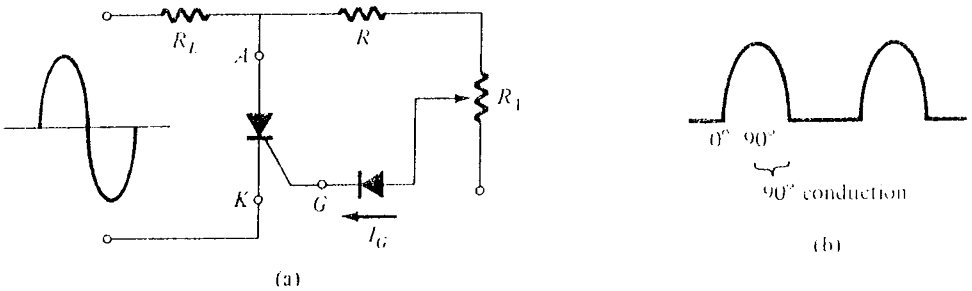


Figure 4.10 Half Wave Phase Control With Thyristor

Now referring to Figure 4.8 when thyristor is off diode is on current flows on diode when, diode and thyristor are off power is stored on the capacitor.Stored energy flow on inductor when thyristor is triggered. Triggering time is not so long to prevent the oscillation to die out.

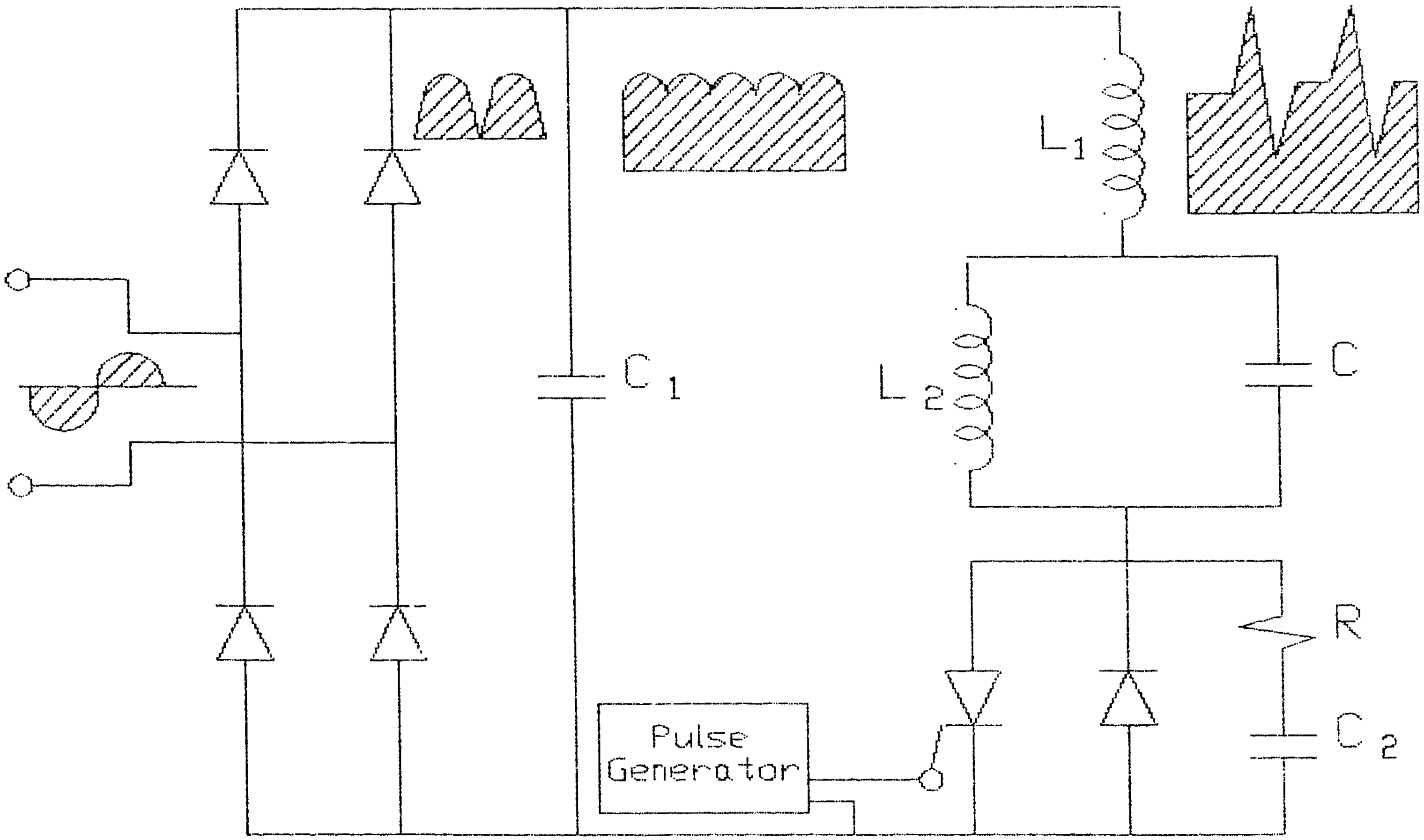


Figure 4.11 Detailed Configuration of Circuit

4.6 Analysis of Induction Heating Circuit

The detailed configuration of the circuit and the current wave forms at each section are shown in Figure 4.11. As in this figure, the complete circuit consists of AC/DC converter, a work coil, an oscillator together with its control unit (thyristor and diode combination and pulse generator)

Alternating current from the main power supply is rectified with a full-rectifier bridge and a direct current is obtained at section (1). A filter capacitor connected across the circuit (C_1) is used to eliminate the ripples on the direct current.

As discussed in the previous section, L_2 and C creates oscillations and these oscillation are controlled by the control unit. Now, considering that the thyristor is turned on , the last part of the circuit can be represented in manner shown in Figure 4.12. The relationship between the input voltage V and the voltage across the tank capacitor can be obtained from following analysis.

The time dependent voltage equation of capacitor and inductor are;

$$V_L = L\frac{di}{dt} \qquad (4.10)$$

$$V_c = \frac{1}{C}\int i \, dt \tag{4.11}$$

Since L_2 and C are connected in parallel, the equivalent impedance of the tank circuit can be determined by using laplace transform method as:

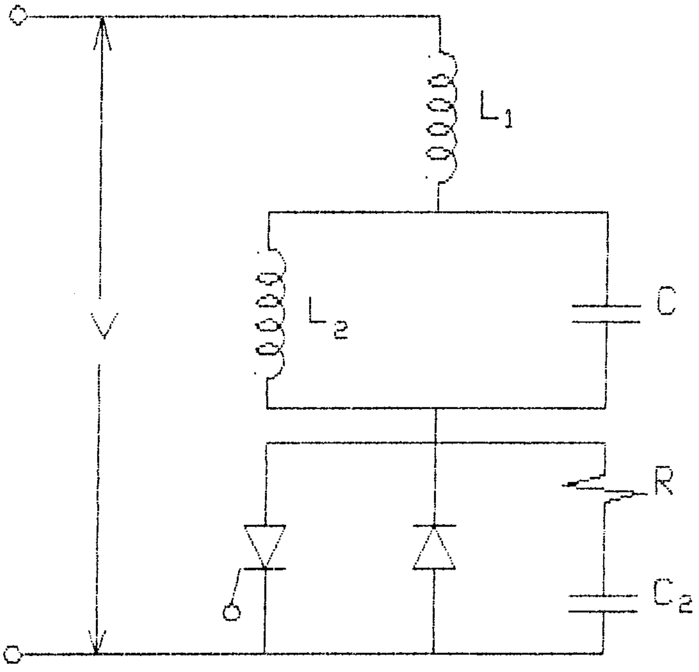


Figure 4.12 Basic Circuit Diagram

$$Z(s) = \frac{L_2 s}{L_2 C s^2 + 1} \tag{4.12}$$

From voltage divider rule the voltage across C can be found;

$$\frac{V(s)}{L_1 s + Z(s)} = \frac{V_c(s)}{Z(s)} \tag{4.13}$$

$$V_C = \frac{VL_2}{L_1L_2Cs^3+(L_1+L_2)s} \tag{4.14}$$

This equation can be rewritten in partial fraction form as:

$$V_C(s) = \frac{VL_2}{L_1+L_2}\,\frac{1}{s} - \frac{(VL_2)(L_1L_2C)}{L_1+L_2}\,\frac{s}{s^2+\sqrt{\dfrac{L_1+L_2}{L_1L_2C}}} \tag{4.15}$$

Taking the inverse Laplace transform of above equation, we obtain $V_C(t)$ as:

$$V_C(t) = \frac{VL_2}{L_1+L_2}\left(1-\cos\sqrt{\frac{L_1+L_2}{L_1L_2C}}\;t\right) \tag{4.16}$$

Here, the frequency of oscillation is:

$$W = \sqrt{\frac{L_1+L_2}{L_1L_2C}} \tag{4.17}$$

If $L_1 \ll L_2$ (L_2 may be between 50–100 times of L_1) then, The frequency is expressed in terms of L_1 and C as:

$$W = \frac{1}{\sqrt{L_1C}}$$

Ad also the expression given in equation (4.16) simplified to

$$V_C = \frac{V}{L_1}\left(1-\cos\sqrt{\frac{1}{L_1C}}\; t\right) \qquad (4.18)$$

At resonant frequency impedances of tank capacitor and work coil are equal $X_C = X_L$ so the impedance is $X_L = L_1/C$

At cessation of diode current there still exists an energy on L_2 being transferred to the capacitor. This can be found by using exact formula and integrating it over the cycle where first the thyristor conducts than the diode.

$$I_{L_2} = \frac{1}{L_2}\int V_C dt \qquad (4.19)$$

$$I_{L_2} = \frac{V}{L_1+L_2}\left(t-\sqrt{\frac{L_1L_2C}{L_1+L_2}}\,\sin\sqrt{\frac{L_1+L_2}{L_1L_2C}}\; t\right) \qquad (4.20)$$

At the first half cycle thyristor will be on, diode will be off and at the second half cycle thyristor will be off because the direction of current on the thyristor is reversed. At this instant diode will operate and current flows on it. As the current reverse its direction, if we do not trigger the thyristor at a second time, energy stored in inductor will flow on capacitor simultaneously. Stored energy on the inductor L_2 is

$$P = \frac{1}{2} L_2 I_{L_2}^2 \qquad (4.21)$$

The current flows on the inductor is obtained from equation 4.18.

$$I_{L_2} \simeq I_o = \frac{V}{L_2} 2\pi\sqrt{L_1 C_2} \qquad (4.22)$$

When thyristor is triggered, this stored energy flows through thyristor. If triggering time is so long the energy stored on capacitor will be subtracted from source affectively and oscillation will die out. If this time duration is not so long, the energy stored in the capacitor will be added and oscillation occurs. Each time thyristor is triggered the value of the energy on capacitor changes. But after few cycles it reaches to its steady state value.

4.7 Power Requirement

The size of the converter or the power required should be determined on the basis of power density, section size, heating method, and production requirements. The losses in the circuit elements are neglected. Matematical analysises are done for ideal power transmission.

Calculations of the induced voltage, current, and the power converted into heat in the part on the basis of an assumed sinisoidal magnetic intensity within the part are given as follows; Voltage induced around the part is

$$E = \frac{d\phi}{dt} \qquad (4.23)$$

Where ϕ is the magnetic flux through the part and is equal to the flux density multiplied by the cross sectional area of the part, as given in equation 4.5. The flux density B is

$$B = \mu H \qquad (4.24)$$

Where μ is permeability which is changing with temperature, H is magnetic intensity as;

$$H = \frac{I_o N}{l} \qquad (4.25)$$

Considering the unit length of the part, resistance to the flow of current around the part is,

$$R = \frac{\rho l}{A} \qquad (4.26)$$

Where, ρ is resistivity of part, l is the length of heated part, A is the crossectional area , so the induced current is written as

$$I = \frac{E}{R} \qquad (4.27)$$

The power converted into heat is then obtained

$$P = I^2 R \qquad (4.28)$$

CHAPTER 5

EXPERIMENTAL SET-UP AND RESULTS

5.1 Introduction

In this chapter, the set-up designed and constructed for induction hardening is explained. Results of experiments performed with this set-up are presented.

5.2 Set-up

The set-up consists of power suply, an AC to DC converter, an oscillator (tank circuit), a work coil, a pulls generator,a control unit and a feeding mechanism.

High voltage alternating current (220 volts) is controlled by variac that is used as power suply. Input alternating power is increased or decreased manually by changing the voltage level.

In AC to DC converter unit, the alternating current is converted to direct current by full wave bridge rectifier. Rectifier circuit is filtered by a by-pass capacitor. Large values of the capacitance provide less riple and higher average voltages. The filter action is shown in Figure 5.1

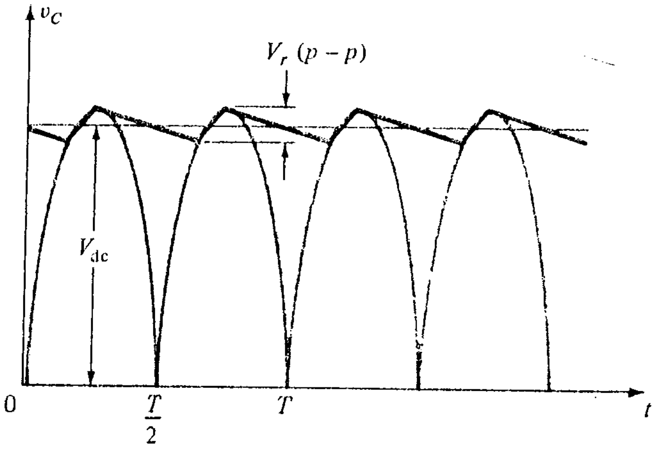


Figure 5.1 Approximate Output Voltage of Capacitor Filtered Circuit.

Converted direct current is oscillated by the tank circuit which consists of a capacitor and an inductor which are connected in parallel. For tank coil 3 mm diameter cupper wire is used. As discussed in Chapter 4, the capacitance of tank capacitor plays very important role on the frequency of the current.

For high frequency applications, the capacitor must have small capacitance while providing large power. These requirements can only be met by a specially designed one and it is bought from one of the leading manufacturers in Turkiye. It has 5 μf capacitance, and designed to work in the frequency of range of 0 to 15 KHz and it is cooled by water. The shape of the produced wave by the oscillator shown in Figure 5.2.

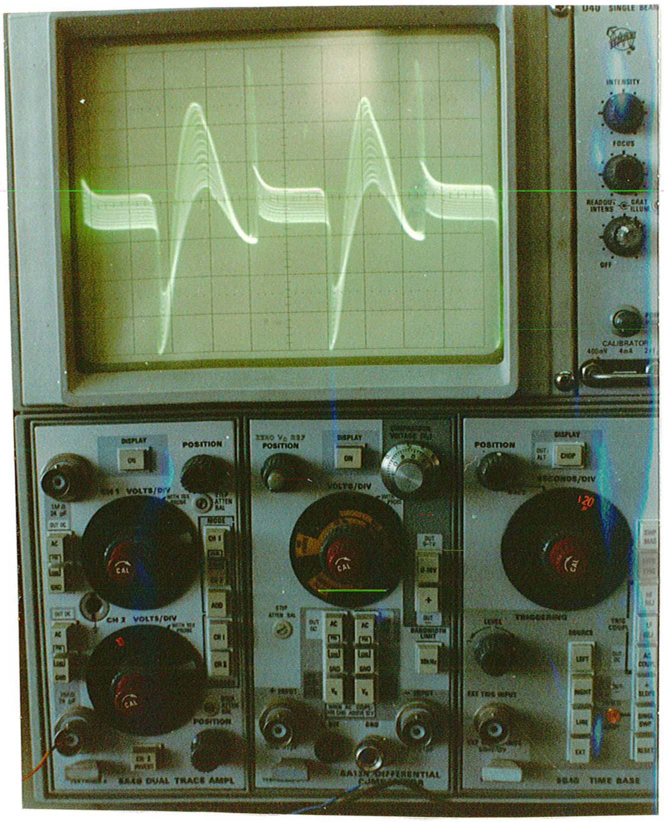


Figure 5.2 Shows the Wave Which is Produced by Oscillator.

The control unit in circuit arrangement is used to control the output of the oscillator. Pulse generator is used to control the thyristor gate by square wave.

The circuit diagram is shown in Figure 4.11 and constructed set-up is shown in Figure 5.3. In this apparatus, there is a feeding mechanism which is designed for through heating and hardening. It is driven by a DC motor. Power is transmitted from motor to power screw by worm-gear reduction. The work-piece is located in the vice mounted on the power screw and is fed through the work coil.

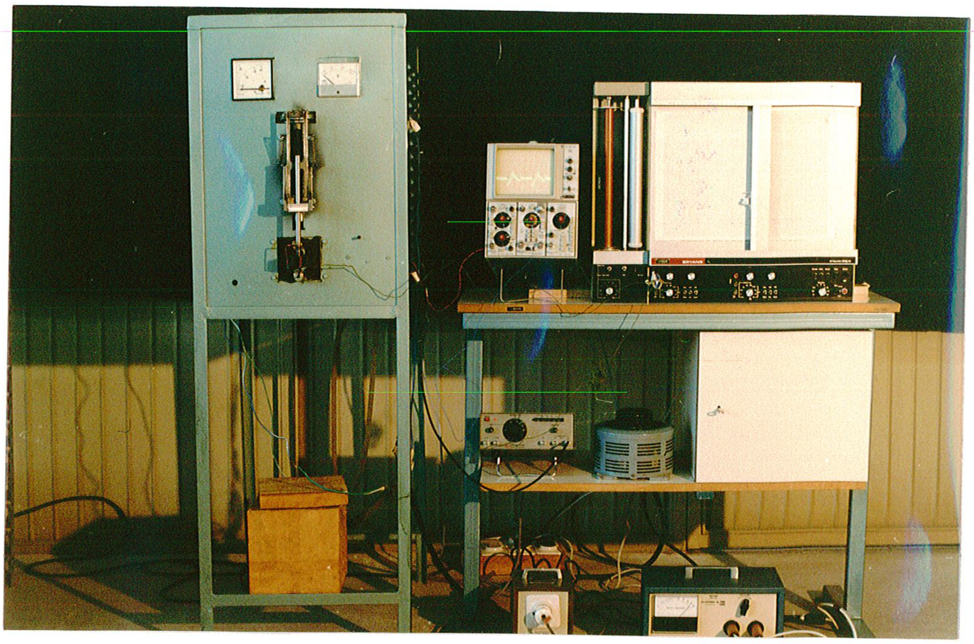


Figure 5.3 Constructed Set-up

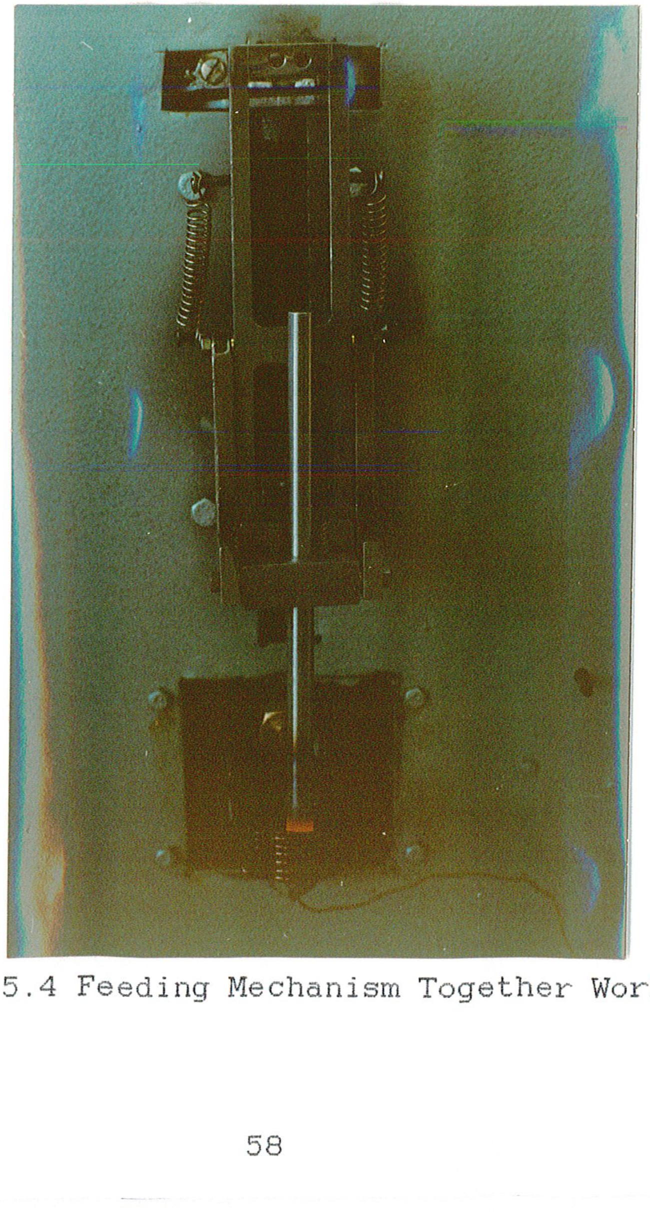


Figure 5.4 Feeding Mechanism Together Workpiece

As shown in Figure 5.4, the graping force in the vice either may be generated by electromagnetic action or by a tension spring.

5.3 Experiments

This section is presented to illustrate the use of the designed set-up and also to verify that how valid the results obtained with this apparatus are . For this purpose, experiments with specimens made of 1060 carbon steel at different diameters are performed. The hardenability and TTT diagram of 1060 steel are shown in Figure 5.5. Specimens with 6, 8, mm, diameters are hardened at different frequencies. During each experiment frequency and voltage are kept constant.

The same work coil is used throughout the experiments. This is to evaluate the affect of air gap between the work piece and the work coil. Work piece is held at the center of the coil. After locating the work piece, power is applied and the required voltage is applied manually. Frequency of the pulse generator is fixed at a certain value.

The temperature of work piece during heating and cooling are measured by using thermocouple and temperature variation with respect to time are plotted by the plotter shown in Figure 5.6. One end of thermocouple is plunged into ice and other end. is

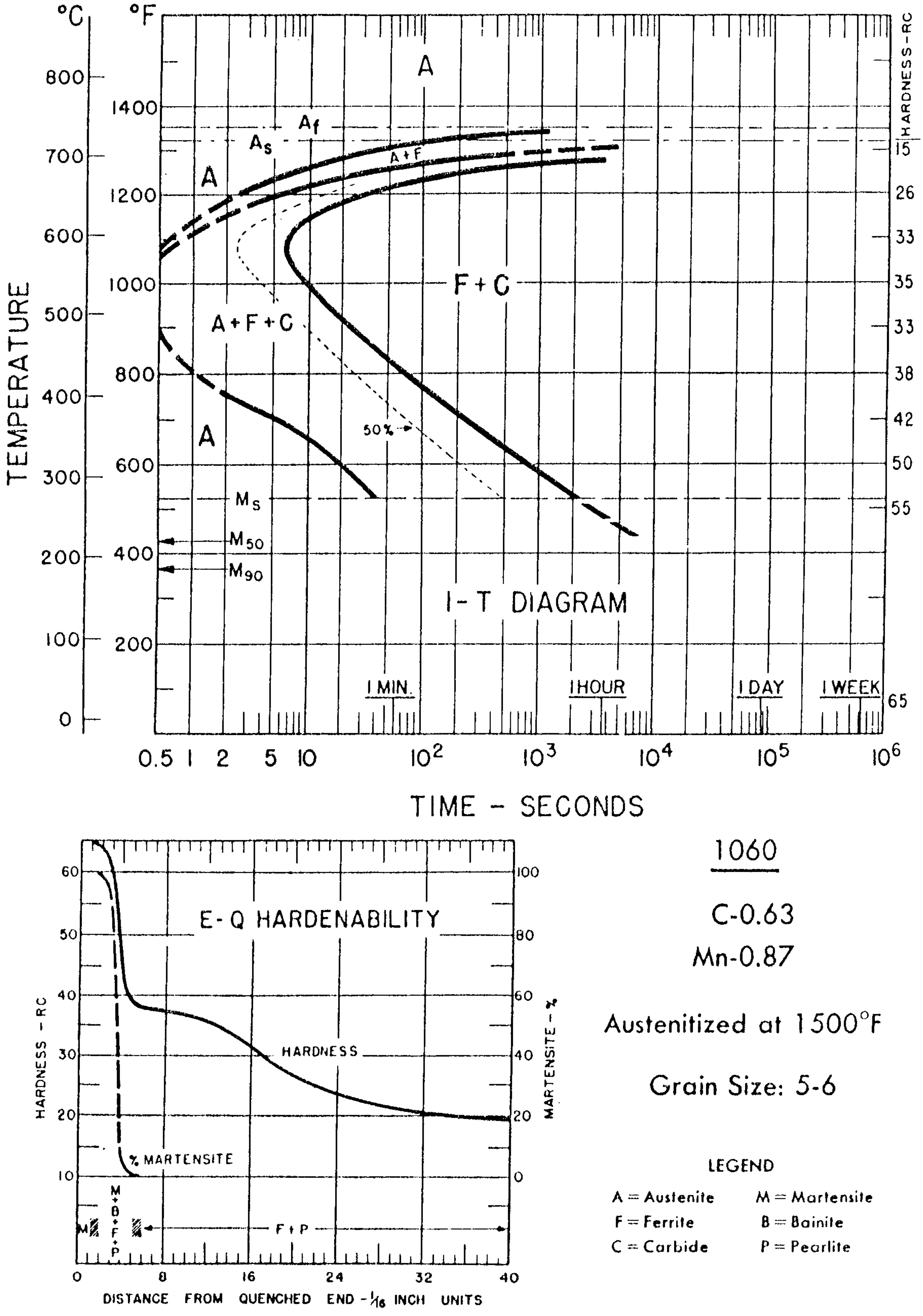


Figure 5.5 TTT Diagram of 1060 Steel [19]

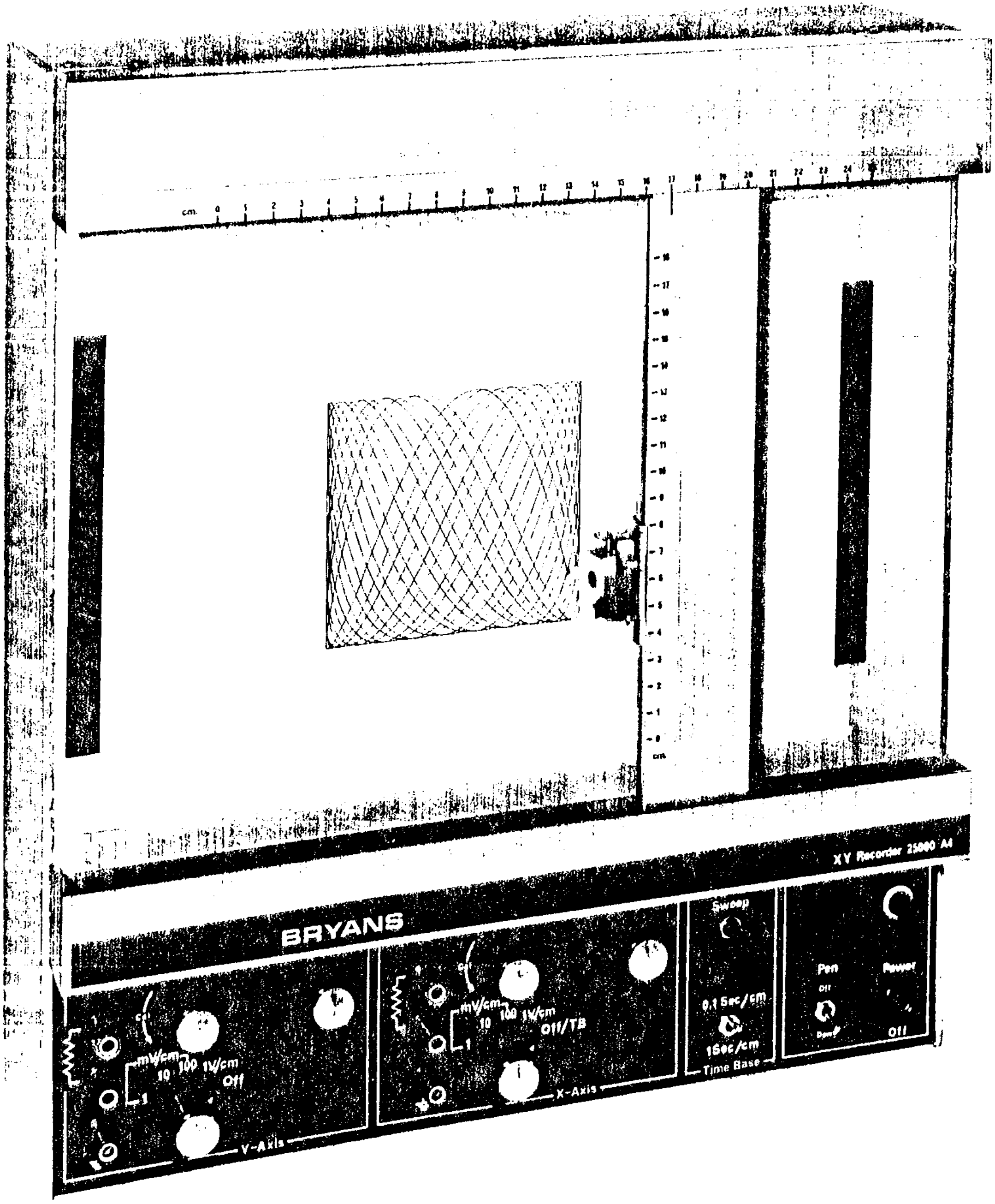


Figure 5.6 Top View of Recorder

welded on the work piece by BHL spot welding machine. When temperature of the work piece is increased above the critical temperature (Austenitic temperature), the work piece is dropped into the water.

After work piece is quenched, hardness of quenched layer measured along the axis of the work piece. Hardened section is taken as a test specimen. It is polished after it is embedded into plastic and then hardnesses of prepared specimen are measured along the surface to core by LEITZ type machine. Micro structure of the hardened work piece is shown in Figure 5.7.

5.4 Results

Figure 5.8-5.9 illustrate the variation in the depth of hardening for the work pieces at different diameters. The variation of the depth of hardening under different frequencies of the work-pieces constant are illustrated in Figures 5.10,-5.11.

The effect of the size of the work piece is investigated at constant frequency and the variation of heating time, current, are illustrated in Figures 5.12-5.13. The affects of frequency is investigated by keeping the size of the work piece constant. Figures 5.14-5.15 illustrate the variation of heating time and current with respect to frequency.

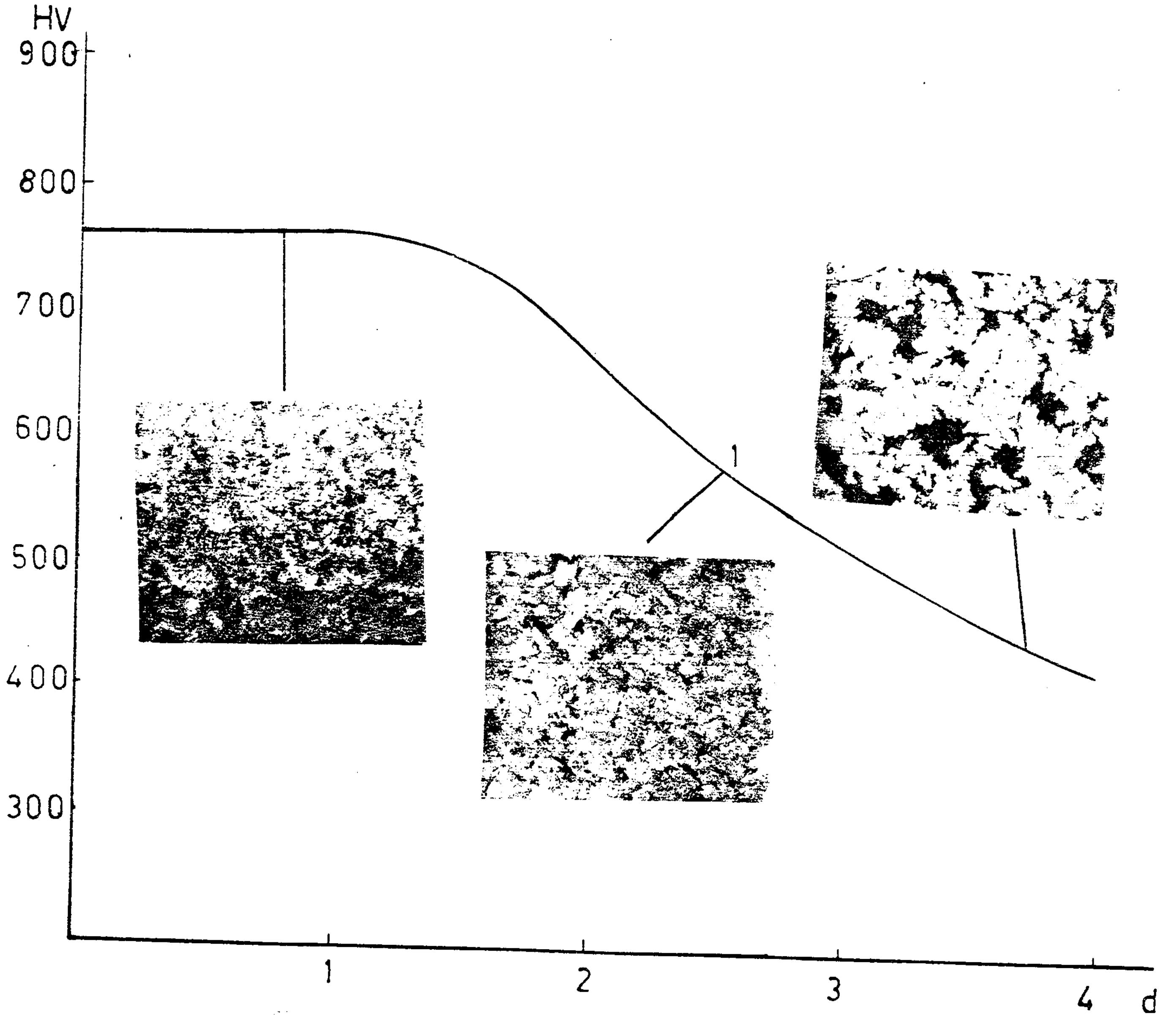


Figure 4.7 Micro Structure Hardened Part

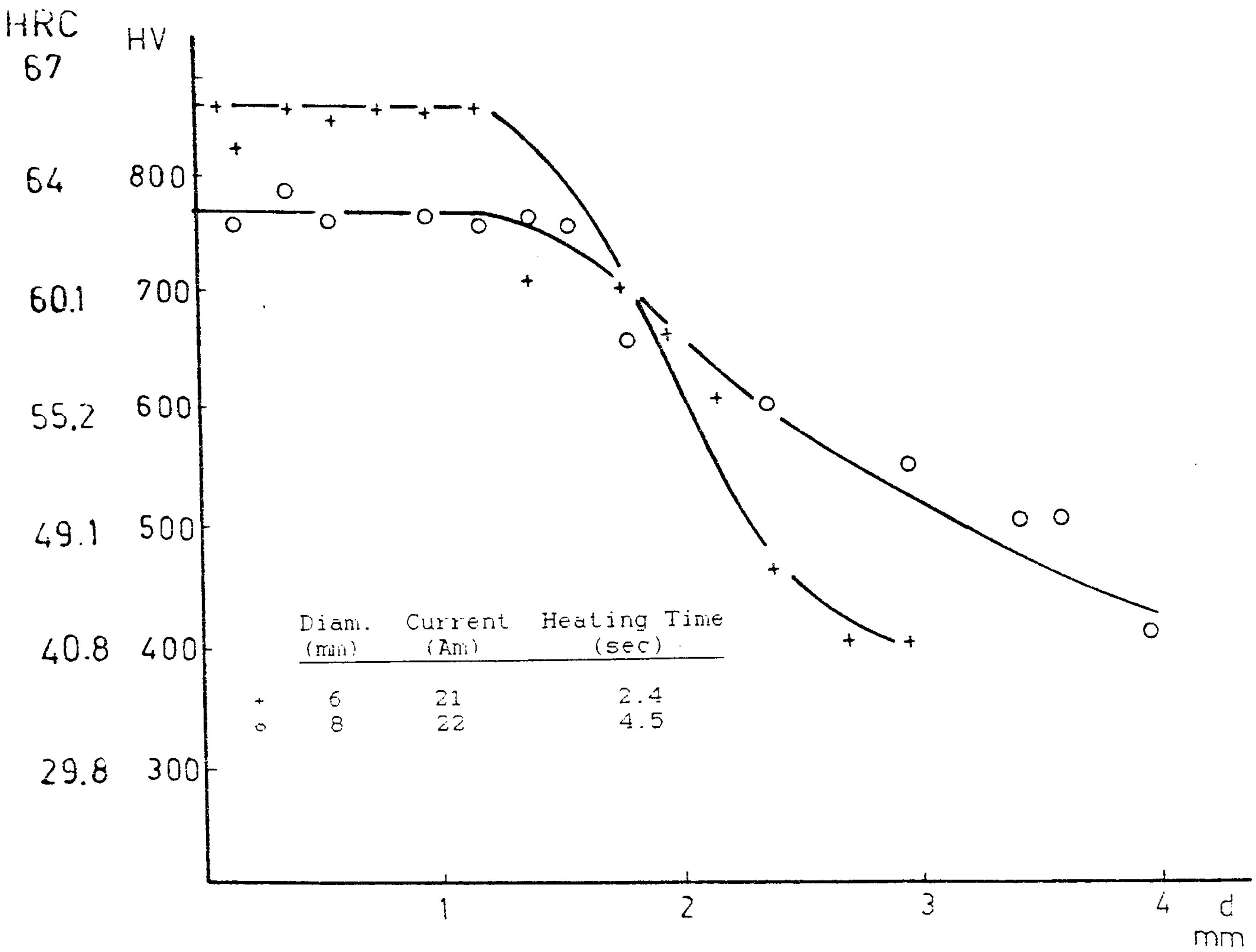


Figure 5.8 Hardness Curves of Specimens Hardened at 8 KHz

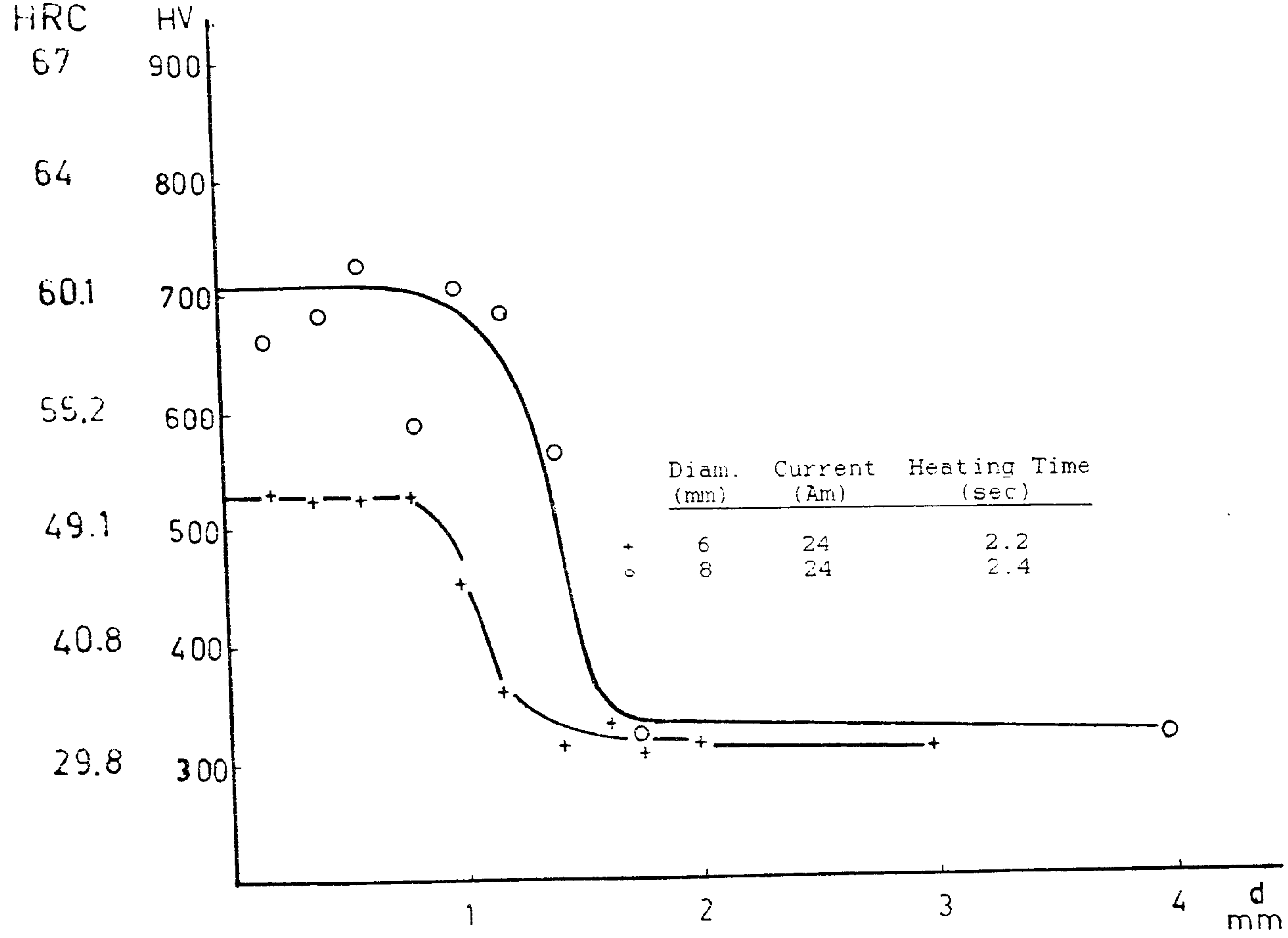
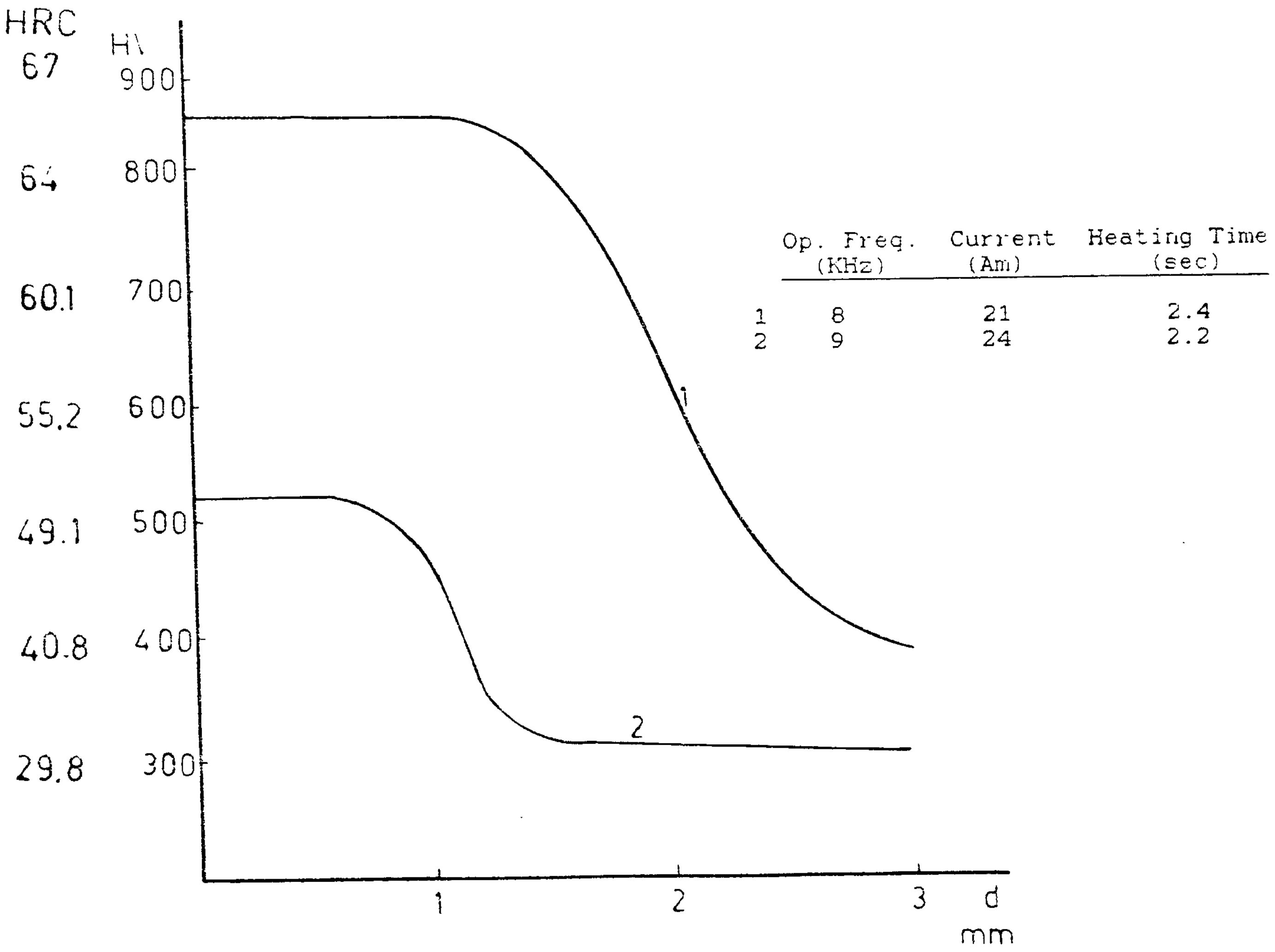


Figure 5.9 Hardness Curves of Specimens Hardened at 9 KHz



	Op. Freq. (KHz)	Current (Am)	Heating Time (sec)
1	8	21	2.4
2	9	24	2.2

Figure 5.10 Hardness Curves of Specimen d=6 mm

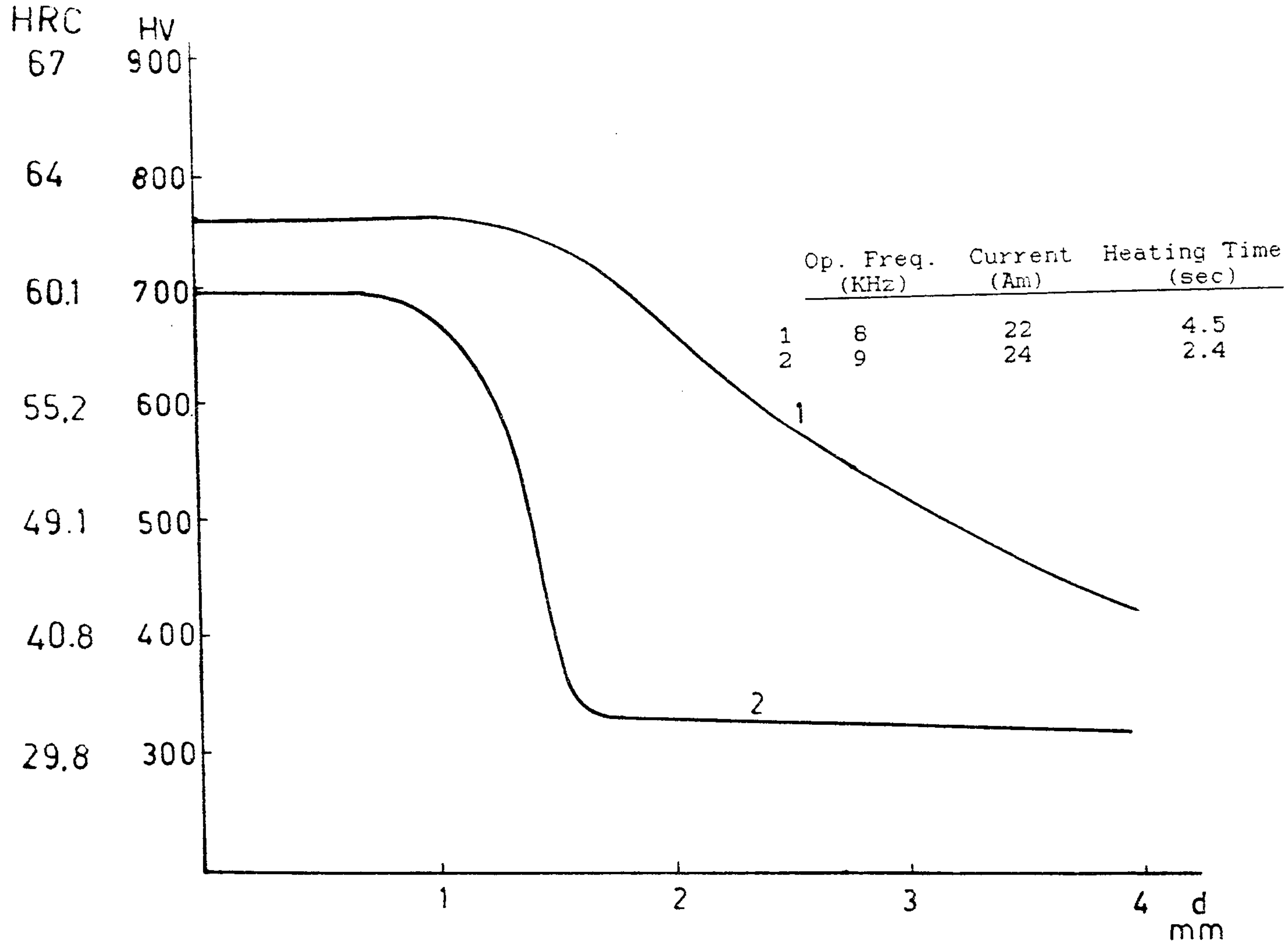


Figure 5.11 Hardness Curves of Specimen d=8 mm

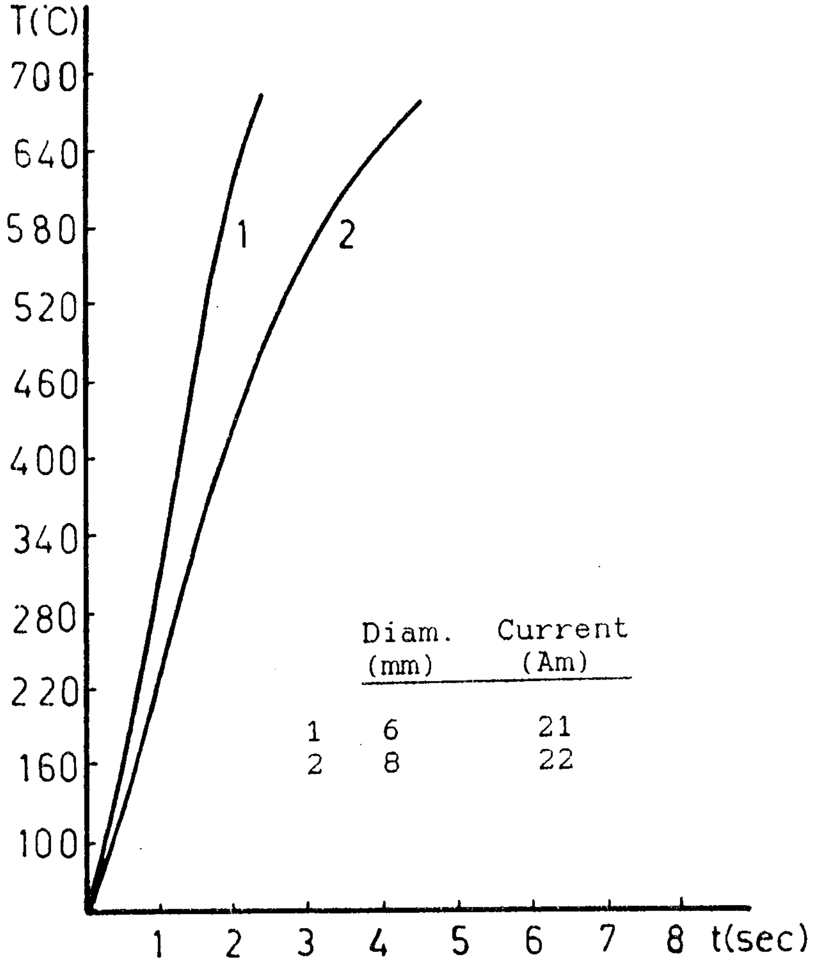


Figure 5.12 Heating Curves of Specimens at 8 KHz

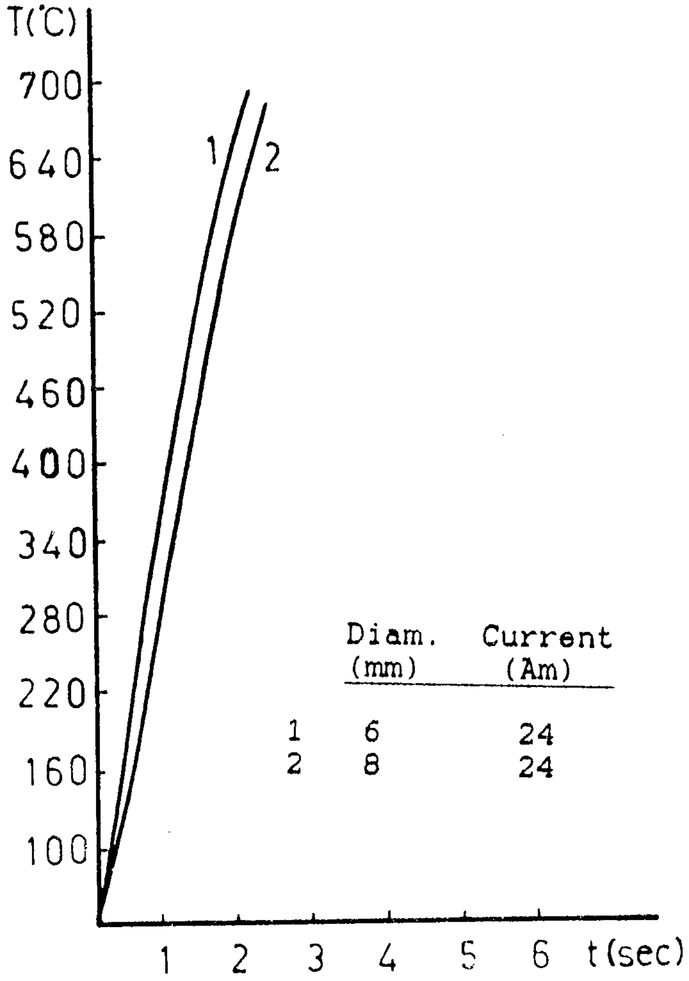
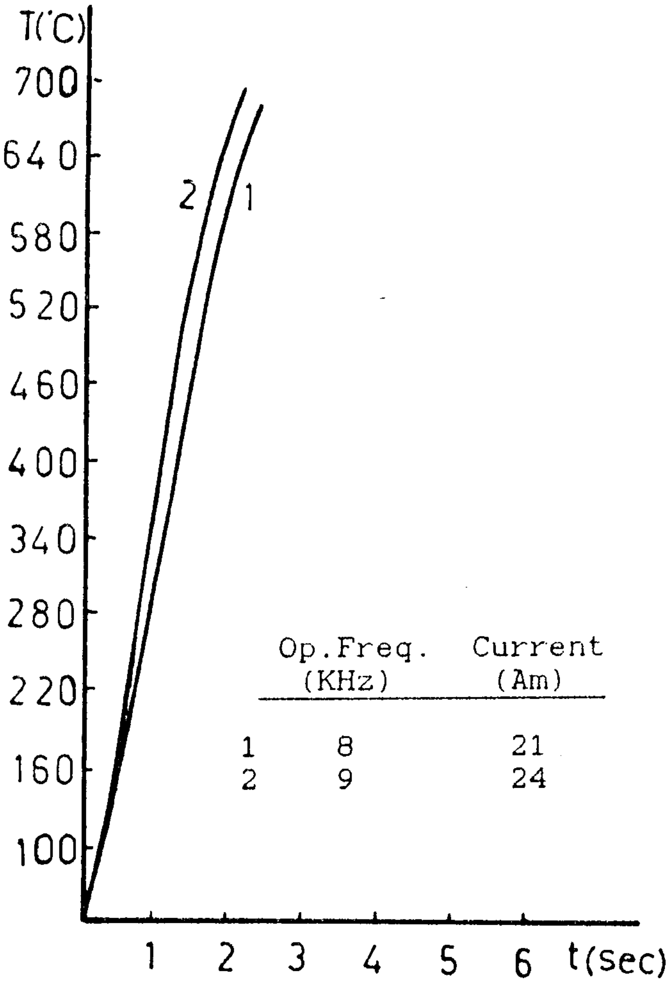
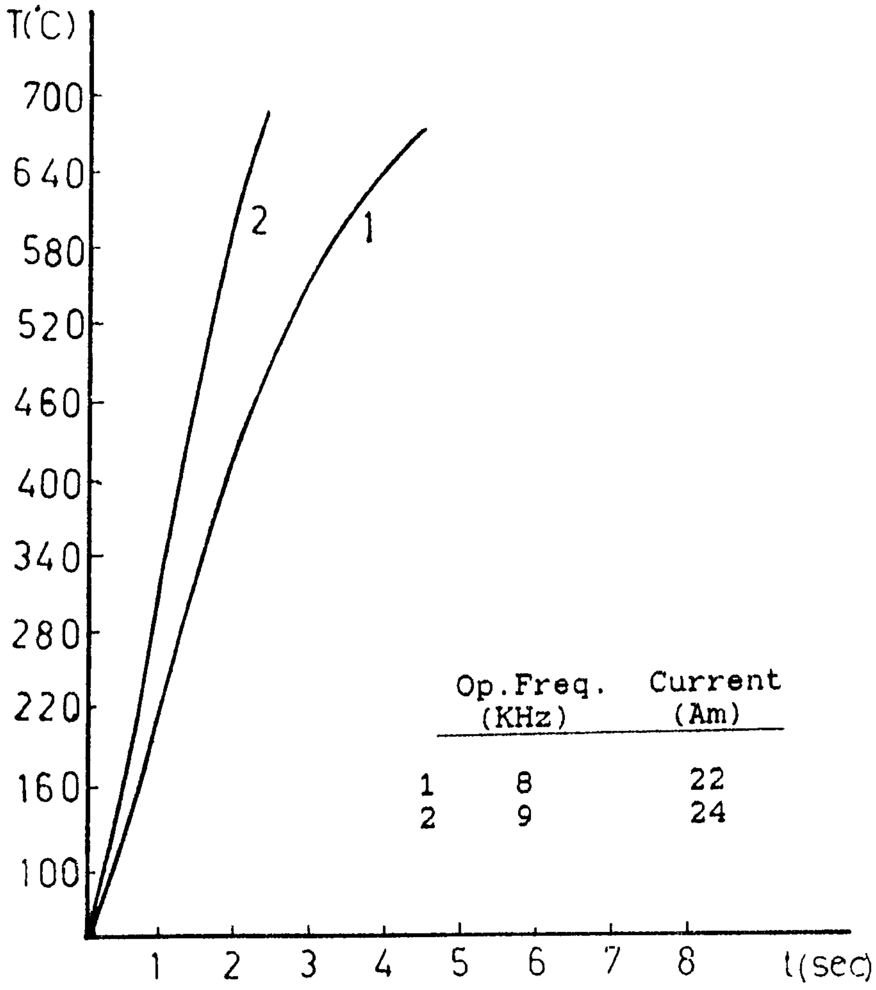


Figure 5.13 Heating Curves of Specimens at 9 KHz



Figures 5.14 Heating Curves of Specimen d=6 mm



	Op.Freq. (KHz)	Current (Am)
1	8	22
2	9	24

Figure 5.15 Heating Curves of Specimen d=8 mm

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1. Introduction

The problems faced in the construction of the set-up in performing the experiments are discussed in section 6.2. Conclusion of this study is given in section 6.3. Section 6.4 is devoted to the suggestion for future work.

6.2 Discussion

The methods of surface hardening were discussed and the advantages and disadvantages of induction surface hardening method were presented in the previous chapters. The initial cost of induction surface hardening was mentioned among its disadvantages. It was actually this reason which has motivated such a study in our department. We have tried to construct the machine at a reasonable cost. All the components used in the circuit were obtained from the markets in Gaziantep except the tank capacitor. This is a specially designed capacitor and produced by one of the manufacturers in Istanbul. It is special because it has to work in a high frequency range while providing large amount of power.

In this study full-wave bridge rectifier circuit is used. In order to prevent damage to the thyristor and diode in the circuit a full-wave bridge rectifier is used instead of half-wave rectifier circuit as AC to DC converter. Rectified Current is not exactly direct current. It has high ripple. High capacitive capacitor is used for filtering rectified current.

The series single SCR inverter was chosen for its simplicity and relatively low cost. It works exceptionally well with today's power semiconductors. The characteristics of the thyristor used in the circuit are 600 volt, 150 amp. and 10 μsec triggering time.

Tank coil is wound from copper wire with the three terminal for which providing flexibility to the other circuit components.

Depth of penetrations obtained from the experiments are quite different from the values calculated by using equations (3.2, 4.1 and 4.2). Because these equations are empiric and some factors like air gap are not considered in these equations.

The experiments were performed with C1060 steel. As can be seen in Figures 5.10-5.11 the depth of hardening changed with the frequency. When frequency is increased case depth of the work-piece is decreased as expected.

For the work-piece of 6 mm diameter, the case depths of 0.8 mm at 9 KHz and 2 mm at 8 KHz are obtained. For the work-piece of 8 mm diameter case depths of 1.2 mm at 9 KHz and 2 mm at 8 KHz are obtained. Both the size and the frequency are affective on the case depth but frequency affect is more dominant.

As can be seen in Figure 5.8-5.11, the levels of heating time changed with the frequency. When frequency is increased heating time is decreased. This was also as expected. The temperature level reached for each specimen are slightly different as illustrated in Figures 5.14-5.15. The main reason of this fact is due to mismatch of the impedances of the work coil and the tank capacitor.

The hardness at the surface of the specimens are given in Figure 5.10-5.11. As it can be seen in these figures, the level of hardnesses of 8 mm specimen do not differ much (approximately 65 HRC) for the frequencies of 8 and 9 KHz. But for 6 mm diameter, the hardnesses at 8 and 9 KHz are different and at 9 KHz, the specimen has the hardness of 50 HRC. This is a contradiction and it was first thought to be the result of small heating time and low heating temperature. To check whether this situation is due to mismatch of the circuit elements or not, it was decided t o perform a series of experiments in a furnace in materials laboratory. Three specimens at 6 mm diameter made of 1060 steel are hardened by heating temperatures for the duration of 30 mm at 800°C, 750°C and 700°C respectively. The hardnesses of these specimens were measured as 60 HRC, 25 HRC and 20 HRC. These experiments validated the above mentioned reasons of low hardness of 6 mm diameter specimen in induction hardening.

During the experiments, we have used the same coil as to see the effect of the air gap on the hardness value as well as on the heating time. From the results given in Figure 5.12-5.13, it is not possible to produce a clear statement on the effect of air gap. For producing a clear statement, several experiments can be done with different coil diameter and with same work-piece.

6.3 Conclusion

In this study, the induction surface hardening method is presented and an apparatus which can be used for this purpose is designed.

The induction surface hardening method is preferable for those machine elements which are subject to high impact loads and are required to have high wear resistance and high fatigue strength.

The main purpose of this thesis was to design and construct an induction surface hardening set-up with the components available in the market in Türkiye. These machines are usually imported and Türkiye is in a situation of paying a lot of money to foreign countries. For this fact, we have tried to show that such machines could be produced in our country with the least available components like capacitor and thyristor.

We would not say that this machine is complete. It needs some modifications, but we could say that with the developments to be made, this machine can be adapted as to give answers to the needs of small scale industry (like valve manufacturing) in Gaziantep and in any other part of South Eastern Anatolia.

6.4 Suggestion for Future Work

As was stated above, this set-up is not a complete one. It needs some modifications. These modifications may be summarized as:

-A capacitor with variable capacitance may be designed. This necessary to increase the range of frequency that could be provided by the oscillator.

-Frequency may be controlled by designed electronic circuit. This is prevent the cut of circuit itself. When temperature is increased the frequency is decreased.

-Temperature may be controlled by an electronic circuit operation. When temperature is raised to above critical range, heated part may be quenched automatically.

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