CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The use of electron beams and laser beams in surface treatment have opened up new industrial possibilities that can lead to finished product quality improvement. These beams, which can concentrate energy on very small area, produce power densities three to four times the order of magnitude higher than conventional processes. This results in special interactions between the beam and the workpiece leading to thermal cycles and consequently to metallurgical characteristics those are difficult to produce with conventional processes.

High energy density infrared light beams complement advantageously the conventional process of treatment. A large number of applications to complex geometrical forms, which are difficult to treat by conventional means, can be handled successfully with beam techniques [5]. The use of high power density heating sources for the localized surface treatment of components offers the potential for energy efficiency, low distortion and higher rates of self-quenching which yield useful metallurgical microstructures [6].

Laser transformation surface hardening or laser hardening is an autogenous method of producing wear-resistant patterns on discrete surface regions of the components. A shaped laser beam is scanned across the surface of component to heat without any melt. A temperature rise of about 1200° C is ideal. The underlying bulk material acts as efficient heat sink for the damped energy, and causing rapid cooling. The hardness, strength, wear, fatigue and lubrication properties of the surface can be improved, while desirable bulk properties such as toughness and ductility remain unaffected [7].
Laser surface hardening is an industrial treatment used to provide hardened surfaces in iron and steel through a solid-state transformation [8]. Ferrous alloys are particularly suitable for laser hardening because fast quenching produces hard martensite. Depending on the material, hardness value up to about 1000 Hv can be achieved to a depth of around 1.5 mm, before surface melting occurs [9]. The process may be used for other materials in which a hardening phase change is induced by a thermal cycle [7].

Until the mid-1990s, only CO$_2$ lasers were able to deliver the power density required for economic rates of hardening large areas. Then Multikilowatt Nd:YAG and (a few years later) diode laser sources became available, which produce beams that are absorbed more readily by the metal surfaces, resulting in improvements in process efficiency and which led to an increase in the scope of application for its pulsed form. The principal objective of laser hardening is to produce a surface with a required hardness to a prescribed depth with the highest coverage rate possible [6].

Over the past few years a considerable number of research papers have been reported dealing with experimental and theoretical aspects of laser hardening. J Dutta Majumdar et al [4] has given overview of the processes by laser beam. John C Ion [9] and E G Donaldson [19] presented comprehensive review of all aspects of laser hardening.

A comprehensive review of all aspects of laser processing has been given in three books by S Martin von Allmen et al [1], John C Ion [7] and John F Ready [11]. Number of authors has published books to cover various fundamental and applied aspects of laser processing; prominent among them are N Rykalin et al [2], W M Steen [5], J C Ion [7] and John F Ready [11]. Since this thesis addresses theoretical and experimental studies on laser transformation hardening, only directly or indirectly related work appearing in the literature is presented.

The topics through literature survey findings are arranged for discussion as follows:

- Principles and practice of laser hardening
- Properties of hardened materials
2.2 Principles of laser transformation hardening

The principles of laser hardening are similar to those of conventional hardening. The time scales involved in the former are, however, typically an order of magnitude shorter. Conventionally heating is induced by a furnace, flame, arc or induction coil, whereas in laser transformation hardening the laser beam is shaped into a suitable pattern and scanned over the component.

![Diagram of laser hardening](image)

**Fig. 2.1 Principle of laser hardening: thermal cycles at two points in 0.35% C steel [9]**

The surface is heated rapidly to a temperature between a critical solid-state transformation temperature and the melting temperature. This is illustrated for carbon steel in Fig. 2.1. The large volume of adjacent material acts as an efficient heat sink, which cools the surface rapidly. Surface hardening is achieved through phase transformations, notably the formation of martensite in ferrous alloys. The structural
properties of the bulk material, such as toughness and fracture resistance are retained, thus producing an ideal composite structure [9].

Induction hardening is growing because it is a fast and clean method well suited for on-line applications in the workshop. Laser hardening has many features common with induction hardening. M Melander et al [10] developed computer programs for induction hardening and laser hardening and some results obtained with them. The experimental results in some cases are comparable.

2.2.1 Beam-material interaction

During solid-state transformations laser heating, the fraction of the beam power absorbed depends on the absorptivity of the material surface [11]. In uncoated ferrous alloys, the photons of the laser beam interact with free electrons in the substrate in a layer approximately 100 μm thick. Energy is transferred into bulk of the substrate by classical thermal conduction. Absorption of the laser beam may be increased by the application of an absorbing layer [9].

In many cases, the absorptivity is relatively low, especially for CO₂ laser radiation. Special absorption coatings such as graphite and molybdenum disulfide through a thin layer of paint have been shown effective since most organic materials have high absorptivity for CO₂ laser light [11].

In many industrial applications of lasers, material processing relies on the heating effect due to absorption of high-power beams incident on opaque mediums. The process of laser-material interaction is fairly well studied and can be adequately described in a wide range of power densities up to 10⁹ W/cm² in terms of the heat model, by which one can conditionally divide the process of laser interaction into a few characteristic stages:

(a) absorption of laser beam and conversion of its energy to thermal lattice vibrations;
(b) heating without material damage;
(c) onset of vaporization in the interaction region and scatter of disintegration products; and 

(d) cooling (quenching) after the laser interaction ceases.

Along with these stages, diffusion and chemical processes take place and phase transformations occur, which have a considerable effect on the character of laser-material interactions. The amount of absorbed energy depends on the optical and thermal properties of materials, especially on the properties of metals and it decreases with increasing wavelength [2].

2.2.2 Composition and Microstructure

Steels exist in a number of polycrystalline forms depending on chemistry and temperature. At room temperature, plain carbon steels contain a mixture of a body-centered cubic phase (ferrite) and an iron carbide phase. Upon heating to a considerably high temperature, the carbides and ferrite dissolve into a single face-centered cubic phase called austenite. The temperature involved are usually between 750° C and 1000° C depending on the chemistry of the steel [11].

The main property required of a material for laser hardening is solid-state transformation, which takes place within typical time scales. The transformations of austenite to martensite in ferrous alloys make these materials particularly suitable for laser hardening. The surface hardness depends on the hardness of martensite formed. It increases linearly with carbon content, from 300 Hv at 0.05% C to about 750 Hv at 0.5%C. However, when the carbon content lies about 0.6%, austenite is retained at room temperature, which reduces the hardness. It is important to note that these limits on carbon content are affected by the presence of other alloying additions; both are reduced by manganese, chromium, nickel and molybdenum. It is also important to appreciate that microstructure are rarely homogenous and that local concentration peaks occur, which may lead to localized austenite retention or even melting.
The phase transformations that occur during laser heating of ferrous alloys are strongly dependent on the initial microstructure of the alloy being treated. Fine morphologies, such as pearlite colonies, quenched and tempered microstructures respond well to laser hardening since sufficient time is available for the dissolution and homogenization of carbon. In contrast, in coarse microstructure, for example the graphite nodules and ferrite matrix of certain cast irons, it may not be possible to achieve sufficient carbon dissolution to affect any appreciable degree of hardening [9].

2.2.3 Phase transformation in heating

The laser beam induces rapid thermal cycles in surface regions of the substrate. Equilibrium phase diagrams can be used to estimate critical transformation temperature on heating. However, during laser heating, phase transformation take place under conditions far from equilibrium. Heating rates of the order 1000 Ks^{-1} are common, and steep temperature gradients are present. Superheating of phase transformation temperature is therefore observed [9].

Only the material immediately adjacent to the heated surface is affected and deeper layers of the material are not heated to the point of austenite formation. The cool martensite under the heated layer also provides a path for rapid heat transfer by which the heated material is very rapidly cooled. This rapid heating of surface layer to form austenite followed by the rapid cooling of austenite, is the characteristic of laser heat treatment, and is unique to that process. Similar effects can be achieved with induction heating and electron beam heating, but laser heat treatment is particularly effective in cost-effective formation of thin-layer heating in localized areas [11].

2.2.4 Microstructural homogenization

In ferrous alloy materials, the formation of homogenous austenite facilitates hardening by distributing carbon uniformly to transform martensite on cooling. The extent of austenite homogenisation is dependent on the kinetic effect of thermal cycle
experienced at a given point in the heated region. The kinetic effect is essentially a measure of the amount of diffusion that occurs during the thermal cycle. Homogenization of austenite may be controlled by diffusion of carbon; from dissolved pearlite colonies in hypoeutectoid steels or diffusion of metallic elements from dissolving carbides in highly alloyed steels. Inhomogeneous austenite, undissolved carbides (particularly those containing metallic elements) and untransformed ferrite are present in regions of the substrate that experience a small kinetic effect. The amount of austenite grain growth is also dependent on the kinetic effect, and is typically very limited during the rapid thermal cycle experienced during laser hardening. Local concentration peaks may lead to local phase transformations, or incipient melting [9].

2.2.5 Phase transformation in cooling

In ferrous alloys, austenite transforms into ferrite, pearlite, bainite or martensite depending on the severity of cooling portion of the thermal cycle. The phase transformations on cooling can be predicted by using appropriate continuous cooling transformation (CCT) diagram. When considering the use of CCT diagrams, it is important to note that they are constructed for a particular prior austenite grain size and since austenite grain growth is limited during laser hardening, a diagram relevant for a small grain size should be used [9].

Under slow cooling conditions, this high-temperature austenite phase reverts to ferrite and carbide structure. The rate of cooling affects this reaction. A more finely divided distribution of carbides in ferrite with increased tensile strength is produced as the cooling rate increases. If the cooling rate exceeds a critical value, the reaction to carbide and ferrite is suppressed and austenite is retained down to much lower temperatures. Processes that produce these rapid cooling rates are often called “quenching”.

If austenite is retained below a critical temperature $M_s$, a structure called martensite is formed. The reaction to form martensite is not time dependent, and depend only the temperature which austenite reaches. The cooler the temperature the greater the
percentage of martensite formed. Because martensite is harder than the other crystalline structures, the result of rapid heating and quenching process is a surface layer with a high value of hardness.

Time-Temperature-Transformation (TTT) diagram shown in Fig. 2.2 is used to indicate the reaction rates and the transformation products produced for 0.8% carbon steel. The two “C” shaped curves represent the time of the beginning and the completion of the reaction of austenite to ferrite and carbide. The values of Rockwell hardness are indicated for the various structures as RC. It is apparent that the martensite has a substantially higher value of hardness than the other crystalline forms [11].

Fig. 2.2 TTT Diagram for 0.8% C steel [11]
The transformation of austenite to martensite is accompanied by a 4% increase in volume, which induces compressive residual stresses in the transformed region, imparting high fatigue resistance. However, high concentrations of carbon and other austenite stabilizing elements such as nickel and manganese reduce the start and finish temperatures for martensite formation, which may result in the presence of retained austenite in the room temperature [9].

2.2.6 Microstructure and properties

The hardness profile of the transformed region is typically characterized by a plateau and a region in which the hardness decreases to that of the base material. The plateau corresponds to a fully transformed microstructure. The gradient represents a range of microstructure comprising fully transformed regions near the surface and untransformed phases and undissolved precipitates close to the transformation boundary, with intermediate regions of mixed microstructure [9].

2.3 Practice of laser transformation hardening

A large number of variables influence the interaction between a laser beam and a material. About 140 such variables can be identified for welding alone. At the finest level of detail, when drawing up a procedure specification, all variables must be fixed within certain tolerances so that processing can be performed repeatedly to a particular requirement.

Successful application of laser hardening requires an understanding of the process and an appreciation of the effects of practical process variables on the properties of the processed material. The principal process variables of laser hardening are shown in Fig. 2.3 [7].
2.3.1 Material properties

2.3.1.1 Composition

A common requirement for surface-hardened components is a minimum hardness of 55 HRC (610 Hv) present to a specific depth. The data of Krauss (1978) indicate that hardness of carbon-manganese steels with carbon content above 0.25% (approx.) meet this criterion. (The presence of alloying additions that promote hardenability may enable this carbon content limit to be reduced.) When selecting a material, it is also important to consider how composition affects thermal properties. As the thermal conductivity of alloys increases, the peak surface temperature decreases, and the depth of thermal penetration in a given time increases. Process variables for hardening of cast iron, for example, must therefore be adjusted to take into account its relatively high thermal...
conductivity and low melting temperature in comparison with structural steels to maintain hardening to a given depth without the onset of surface melting [7].

2.3.1.2 Geometry

The geometry of the component influences the distribution of heat flow. As a thumb rule, the component thickness should be at least ten times the depth of desired hardened region, to enable self-quenching to occur without significant bulk heating effects; the energy source can then be treated as true surface source, and the temperature fields modeled accordingly. Edges are potentially sources of heat built-up. The beam should be kept at a prescribed distance from an edge in order to prevent overheating or melting. This may be achieved by removing the absorptive coating adjacent to the edge or by using a beam with an intensity profile that trails off towards its edge to reduce edge heating. External corners have a large ratio of heated surface area to volume, and so they are prone to overheating. The opposite is true for internal corners [7].

2.3.1.3 Absorptivity

A polished metal surface reflects between 90 to 98% of the incident light of a perpendicular CO₂ laser beam. The absorptivity of the surface must therefore be increased if infrared light is to be used as the energy source, to improve process efficiency and reduce reflection. This can be achieved in number of ways: by directing the beam at the Brewster angle (about 70° from the normal); by preheating the substrate; or by applying an absorptive coating. An aerosol spray coating of colloidal graphite is the most popular means of increasing absorptivity because it can be applied and removed easily with high repeatability. A uniform of layer of 10-20 μm in thickness is optimum, enabling the absorptivity to be increased to over 80%. If the coating is too thin, it will burn off quickly, exposing the substrate, thereby dramatically reducing the absorptivity. If the coating is too thick, vaporization of volatile elements in the spray can affect processing
through the formation of plumes. A shroud of inert gas helps to stabilize the surface condition, maintaining the absorptivity at a constant value [7].

Volodymyr S Kovalenko [12] proposed few techniques to intensify the process and to improve the quality of the hardened surfaces which includes:

i) the development of new absorption coatings to increase laser-radiation absorption efficiency of the surface to be hardened,

ii) the development of device to measure material absorptivity and instant temperature in working zone at laser irradiation conditions,

iii) the new compositions development for alloying and cladding and

iv) the development of combined techniques.

A correct understanding of the absorption phenomenon during laser processing and a careful experimental evaluation of related co-efficient is of basic importance for any consistent modeling of welding and surface treating operations [13].

2.3.2 Beam properties

Though laser transformation hardening is accomplished with relatively low power density, the cross-sectional area of the beam used to scan the part being heat treated is normally much larger than the focused beams used for welding and cutting. For this reason, relatively high beam power is often required for laser transformation hardening. Traditionally, high power CO$_2$ laser beams have been used because of the higher power requirements. Unfortunately, steels have poor absorptivity for CO$_2$ laser radiation. This combination of high power requirement and low absorptivity dictates the use of absorptive coatings.

The power available from Nd: YAG lasers have increased to the degree that they have become more viable candidates for laser transformation hardening. Steels have a much higher absorptivity for Nd: YAG laser beams, making laser transformation hardening practically possible without absorptive coatings for many applications [11].
In Nd: YAG lasers both cavity and system optics can be made using high quality optical glass or fused quartz. In addition, excellent dielectric coatings are available for these materials at 1.06 μm. The CO₂ laser system, however, present a difficult optics problem. Operation at 10.6 μm precludes using conventional optical materials [14].

2.3.2.1 Wavelength

For many years, only CO₂ laser beams were used, which are now replaced by Multikilowatt Nd: YAG and diode lasers, due to improved absorptivity of a metal surface. This simplifies the operation considerably - the cost of applying and removing absorptive coatings can be the factor that makes CO₂ laser hardening uneconomical in comparison with other methods of surface hardening [7].

Each type of laser has certain properties that make it suitable for a particular task. For example, a pulsed YAG laser is smaller in size than CO₂ laser of the same power; it produces shorter-wavelength light that can be better absorbed by metals than longer wavelengths (the carbon di-oxide wavelength is 10.6 μm), it can provide higher peak-to-average power output ratio than pulsed CO₂ types and it makes glass optics simple [8].

The advantages of pulsed mode in laser processing are mainly:

i) The temporal limitations in energy coupling into the target, resulting in a very limited depth of heat conduction into it, often resulting in reduced heating of the workpiece and thus in higher quality and ii) the high pulse peak power and there by high intensity, obtainable resulting in improved light coupling in some materials which enables or improves the processing [15].

Michael B et al [16] carried out finite difference calculations to characterize a periodic alternation of heating and nonheating of finite and semi-infinite regions. Heating with a fixed heat flux density and heating with a fixed temperature at the surface or surfaces were both examined. Periodic on-off heating with a fixed heat flux density is shown to be particularly advantageous when deep and rapid penetration of energy is to be accomplished while constraining the maximum temperature at the surface.
2.3.2.2 Power

The normal power range used is 1-3 kW. A high power level enables high traverse rates to be used, with correspondingly high coverage rates. However, the practical window of traverse rate is then reduced because the risk of overheating, leading to surface melting, or insufficient peak temperature with no hardening, increases. The robustness of the process thus reduces. For these reasons, an incident power of about 1 kW is normally recommended. Materials of high hardenability may be processed with a lower power density and a higher interaction time, in order to achieve a homogenous case depth. Conversely, materials with low hardenability are processed with higher power density and lower interaction time in order to generate the rapid cooling rates required for martensite formation, at the expense of a shallower case [7].

I R Pashby et al [17] used 1.2 kW diode laser for surface hardening of a plain carbon and alloy steel and investigated relationship between laser power and processing speed. The work demonstrated the technical capability of diode laser in surface hardening both the plain carbon and alloy steel with practical case depths being achieved.

R A Ganeev [18] has shown the possibility of using low-power CO\textsubscript{2} laser (100 W) for effective restructuring of steel surfaces and growth in its microhardness. Thus, nowadays, application of low-power lasers in a number of cases (despite smaller speeds of processing) appear to be more favorable in comparison to expensive large-sized powerful (up to 10 kW) CO\textsubscript{2} lasers for these purposes.

2.3.2.3 Power density

A heating pattern may be created by simply defocusing the beam. This is satisfactory solution for many engineering applications. The sectional depth profile of the hardened region can be approximated as the mirror image of the beam intensity distribution; with reduced amplitude and some rounding at the edges from lateral heat flow. Thus, a beam with a Gaussian beam power distribution typically produces a
hemispherical hardened section, and a uniform power distribution produces a rectangular hardened section, with rounded edges.

A uniform distribution of power in the beam profile maximizes case depth, the uniformity of depth and coverage rate. In contrast, ring and Gaussian profiles minimize distortion, although the latter can lead to centerline melting. The optimum distribution of power tailing off towards the trailing edge. This induces a thermal cycle that provides sufficient time for microstructure homogenization, but a sufficiently high cooling rate helps martensite formation. By using such a heating pattern, the energy required to harden unit volume of material is minimized. However, the optics required to produce such a heating pattern are expensive, and so the method is normally reserved for large volume applications [7].

The cross-sectional intensity of the laser beam determines how the energy will be distributed over the surface area which the beam interact. The shape is determined within the laser cavity and many different cross-sectional shapes, known as transverse electromagnetic (TEM) modes, of the field are possible. Subscript suffix numbers are used to describe the distribution pattern. TEM$_{00}$ is the basic mode in which lasing occurs only along one axis with distribution being Gaussian. Such a beam can be focused to a very fine point on the workpiece so giving the highest possible power density. This is most suitable for fine drilling or cutting with a narrow knife. Other modes will spread the power over greater area and may be suitable for other applications such as surface hardening [19].

W Wu et al [20] developed a 3-D numerical model for pulsed laser transformation hardening, in which, spatial and temporal intensity distribution, temperature- dependent properties of material and multi-phase transformations are considered. The influence of laser temporal pulse shape on connectivity of hardened zone, maximum surface temperature of material and hardening depth are numerically investigated at different energy levels. Results indicate that these hardening parameters are strongly dependent on the temporal pulse shape. For the rectangular temporal pulse shape, the temperature field obtained from this model is in excellent agreement with analytical solution.
2.3.2.4 Beam interaction time

A beam interaction time in the range 0.01-3 s is typical of transformation hardening. The length required of the beam in the travel direction is fixed by the power density and track width requirement. Hence, the required transverse rate can be found by dividing the length by the interaction time. Traverse rate is the variable that is normally changed when fine-tuning the required hardened depth and degree of homogenization [7].

L J Yang et al [21] carried out experiments to identify the effect of overlapping runs on DF-2 tool steels specimens. It has been found that overlapping runs may either decrease or increase the hardness of the overlapped areas, and is due to tempering. On the other hand, the increase in hardness in the overlapping area due to the increased interaction time and austenitizing temperature because of preheating caused by the earlier runs.

In another report [22], they have investigated the effect of speed, nozzle gap and power input on the case depth of laser transformation hardened ASSAB DF2 (equivalent to AISI 01) tool steel specimens. It is found that, the case depth increases as either the specimen thickness or power input is increased, but decreases as the traversing speed is increased. The beam diameter, however, does not seem to have a significant influence on the case depth.

2.3.3 Process properties

2.3.3.1 Process gases

Process gas serves two functions in transformation hardening. It shields the interaction zone, thus preventing oxidation, which increases absorptivity and could result in overheating and melting if intensity is not controlled. The process gas also protects the optics from fumes and any other contaminates produced during processing. Argon and nitrogen are common choices since they blanket the interaction zone effectively. Gas
flow rates of around 20 L min$^{-1}$ are normally used, delivered either coaxial with the beam or from an external nozzle.

### 2.3.3.2 Coverage of large areas

When large areas are to be hardened, individual tracks must be placed adjacent to one another in sequence. In such cases, lateral heat flow from one-track results in tempering of the previous track. The hardened surface thus contains bands of softer tempered material. It is normally best to avoid such structures, although in certain applications the softer zones may be useful for retaining lubricant.

Adelin Han et al [23] analyzed the three main variables that are structurally characterizing the laser material processing: the influence factors, the process variables and the objective functions. These variables are divided in subsets determined by the system's structure, operating procedures and objectives of technological transformations as shown in Fig. 2.4.

### 2.4 Properties of hardened materials

The transformation of austenite to martensite in ferrous alloys within the time scales is the basic requirement of laser hardening. The degree of hardenability and fineness in microstructure obtained depend on the laser processing variables i.e. laser power, beam diameter, beam shape, scanning velocity, focusing condition and material chemistry. Many investigations in this direction have been reported and some of them are described as below.

Ferrous materials such as carbon-manganese, low alloy tool and martensitic steels and cast irons are particularly suitable for laser hardening. Attempts have also been made to harden certain non-ferrous materials [9].
Fig. 2.4 Characteristic variables of material laser processing [23]
2.4.1 Carbon–manganese steels

2.4.1.1 Hypoeutectoid steels

The initial microstructure of hypoeutectoid steels i.e. those containing less than 0.8 wt. % C, consists of pearlite surrounded by proeutectoid ferrite. On heating, pearlite transforms to austenite by dissolution of the cementite lamellae followed by growth of the austenite transformation front into regions of high carbon concentration at a rate controlled by carbon diffusion between lamellae. Ferrite transforms by nucleation and growth of austenite at internal ferrite grain boundaries at a rate controlled by carbon diffusion over greater distances is associated with the size of ferrite colonies.

Around the peak of the thermal cycle, the microstructure comprises homogenous austenite near the surface, with banded structures containing carbides; particularly alloy carbides and un-dissolved proeutectoid ferrite at greater depths within the transformed zone. Similar microstructures have been observed in studies of rapid heating and cooling of steels.

On cooling, the microstructure of the transformed region comprises martensite near the surface, proeutectoid ferrite and martensite (containing small-un dissolved cementite plates) close to the transformation boundary and an immediate region of ferrite and carbides in a martensite matrix.

The initial microstructure of the steel has a significant effect on the properties of the hardened region. Pre-treatments, such as normalizing, quenching and tempering and preheating promote uniform distribution of carbon throughout the microstructure, facilitating austenitization on heating and reducing the likelihood of austenite being retained in the retained microstructure. Deeper transformed regions are observed in quenched and tempered steels compared with those treated in the normalized condition.

The effect of laser heat treatment in steels is dependent on the carbon concentration. At low contents the response is low, despite the high quenching rate and care must be taken to avoid entering into the δ-ferrite field on heating because on cooling this δ-ferrite may be retained and hence cannot transform to martensite. On
increasing the carbon concentration the hardenability is increased but above 0.4% C there is difficulty to dissolve the iron carbide and homogenize the austenite in the relatively short heating cycle. In addition, the proportion of residual austenite increases necessitating the additional heat treatment. The influence of carbon concentration is as shown in Fig. 2.5 [24].

![Fig. 2.5 Influence of carbon content][1]

Makoto Hino et al [25] applied high-powered Nd: YAG laser of 1 kW with scanning speed of 1 mm/sec to carbon steels containing 0.18-0.54 wt. % C without the absorbents. The structure of the hardened zone underwent complete martensitic transformation in all of the carbon steels tested, and its hardness increased with greater carbon content. Under identical irradiated conditions, the hardened zone expanded with increasing carbon content. Consequently, in order to obtain a relatively uniform hardened zone, it was important to select the appropriate type of assist gas and flow rate.

E Navara et al [26] studied laser transformation hardening of low and medium carbon steels by using 2.5 kW CW CO₂ laser, in order to establish the martensitic
transformation characteristics during a laser thermal cycle. It is found that the martensitic transformation characteristics and hardness of laser-hardened steels are controlled by the rate at which carbon diffuses during the thermal cycle.

2.4.1.2 Hypereutectoid steels

Laser heating of spheroidal hypereutectoid steels containing globular cementite in ferrite matrix, causes austenite to nucleate at the cementite/ferrite interface in the form of a shell around the cementite. The shell expands by cementite dissolution and redistribution of carbon occurs. Carbon rich austenite subsequently transforms to martensite although austenite regions of particularly high carbon concentration may be retained as concentric rings at room temperature. High hardness values up to 1000 HV have been recorded in such materials [9].

2.4.2 Alloy steels

2.4.2.1 Low alloy steels

Low alloy steels, with total alloy content below 2%, also respond well to laser hardening. Hypereutectoid low alloy steels contain carbon with additions of chromium, nickel, manganese and vanadium to increase hardenability. Although such steels are designed to be through hardened by conventional furnace treatment, they can be laser hardened. Alloying additions raise the maximum hardness that can be obtained and increase the depth of uniformly hardened region in comparison with a carbon manganese steel of similar carbon content.

The carbon content still plays an important role in determining the properties of the transformed region. However, high levels of carbon, in conjunction with alloying additions, mean that austenite is more likely to be retained in the microstructure, reducing the hardening effect. Martensite often appears in a twinned morphology. The addition of carbon lowers the melting temperature and thus limits the maximum depth that can be transformed without surface melting.
I Katsamas et al [27] investigated the use of a laser beam to carburize the surface of DIN 15CrNi6, low alloy by using 3 kW CW CO\textsubscript{2} laser by coating the surface. Significant enhancement of microhardness was observed in the laser carburized specimens, ranging from 2.5 times 4 times the base metal microhardness.

2.4.2.2 Medium alloy steels

Medium alloy steels with alloying additions, between 2 and 10% may be hardened by laser heating although retained austenite is frequently observed in the hardened microstructure. Steels such as 42CrMo4 (AISI4140) are popular material for hardening for which hardness levels around 650 Hv may be obtained. Quenching in liquid nitrogen is one of transforming austenite to martensite, producing hardness values up to 1000 Hv in more highly alloyed steels.

Transformation hardening of a range of medium carbon-chromium steels can result in an improvement between 1.4 and 1.6 times in wear resistance. The fatigue strength of laser hardened 42CrMo4 is comparable with that of carbonitriding treatment.

Zhang Guangjun et al [28] presented the results of the applications of laser transformation hardening to precision slide ways and specimens of 20, 45, GCr15, 18Cr2Ni4WA and other steels by using 1 kW transverse CO\textsubscript{2} laser. It is concluded that, LTH can meet all requirements such as the case depth hardness, case depth, distortion allowance, wear resistance and technical reproducibility of slide ways and therefore recommended as a substitute for conventional heat treatment.

M S Devgun et al [29] studied the microstructural features, hardness, case depth and wear characteristics of laser heat-treated 52100 bearing steel (0.98-1.10\% C, 0.25-0.45\% Mn, 0.15-0.3\% Si, & 1.3-1.6\% Cr). It was concluded that the laser heat treatment resulted both in improved surface hardness and in sliding wear resistance over conventionally quenched and tempered steel. The 1.4 kW axial flow CO\textsubscript{2} laser was used for this purpose.

Gongqi Shi et al [30] studied the microstructure and properties of laser surface hardened M2 steel by using 2 kW CO\textsubscript{2} laser with 1500 W power and spot size 3 mm
in diameter. The influences of preheat treatment processes, post heat treatment processes and laser parameters on the properties of laser heat-treated zone were also investigated. It is found that the hardness of M2 high speed steel increased evidently by laser transformation hardening. It can be further enhanced by an increase in laser power density. The hardness of laser hardening zone is closely related to the preheat treatment process of substrate.

Pedro De Ia Cruz et al [31] studied the effect of laser hardening by using 2.5 kW CO₂ laser with beam power 1500 W, on the fatigue limit, fatigue strength and notch sensitivity of B-Mn steel. The results are compared with the specimens which were with quench and tempering and plasma-nitriding treatment and laser hardening results are better.

2.4.2.3 High alloy steels

Highly alloyed steels, containing more than 10% of deliberate alloying additions, generally respond poorly to transformation hardening compared with other steel types because of the amount of austenite retained in the room temperature microstructure. Hardness can be increased by quenching in liquid nitrogen, although lower values are observed than with medium alloy steels [9].

M Roth et al [32] carried out the hardening of turbine blades 12% Cr steel with a 15 kW laser. It is found that due to variation of the laser processing parameters, power and interaction time, different hardness profiles could be obtained. Hardening with multiple passes showed no significant drop of the hardness between adjacent passes.

2.4.3 Tool steels

2.4.3.1 Oil hardening tool steels

Transformation hardening of the oil-hardening tool steel AISI 01 produces microstructures containing lath martensite with carbides and retained austenite having
a surface hardness in the range 870-940 HV. A more homogenous hardened zone is produced in materials with finer quenched and tempered initial microstructure compared with those in the received spheroidal condition.

2.4.3.2 Air hardening tool steels

As the severity of the hardening treatment decreases by using air hardening, the hardness of transformed region decreases. This is reflection of the effect the alloying additions on the microstructure produced.

2.4.4 Stainless steel

Only martensitic grades of stainless steel contain sufficient carbon to be hardened by laser heating. The degree of hardening is strongly dependent on the initial condition of the steel as well as its chromium content.

2.4.5 Cast irons

The amount of pearlite present in cast irons determines their response to laser hardening. The greater the amount of pearlite results in the higher the hardenability. Variations in composition and thermal conductivity also affect the response of cast irons to hardening. A high thermal conductivity means the surface temperature remains relatively low, and surface melting is likely less. In contrast, high carbon content lowers the melting temperature, which limits the depth that can be achieved before melting occurs.

2.4.5.1 Grey irons

Laser heating can be used to harden most types of grey iron. Graphite flakes can be dissolved during typical thermal cycles because of their high ratio of surface areas to volume. The thermal conductivity of grey iron, with its interconnecting graphite flakes, is higher than that of nodular iron, which means that a relatively hardened case is produced. Heat is transported from the surface to the bulk rapidly
limiting the surface temperature and reducing likelihood of surface melting. This widens the range of acceptable processing parameters. In all cases, the extent of transformation increases with an increase in beam interaction time and an increase in surface peak temperature.

2.4.5.2 Pearlitic grey iron

Pearlitic grey iron is relatively easy to harden because the pearlitic matrix readily transforms to homogenous austenite on heating. On cooling, the surface microstructure comprises coarse martensite, retained austenite and undissolved graphite flakes with rims of ledeburite where incipient melting occurred. The amount of retained austenite decreases at greater depths, while the amount of incompletely transformed pearlite increases. Cementite lamellae, martensite, carbides and ferrite are observed at the base material. Surface hardness values up to 1000 Hv have been reported, although values that are more typical are in the range 700-900 Hv in regions where austenite is retained. Coarse martensite is observed with retained austenite in the regions of high carbon content. Rims of ledeburite are observed at the edge of the flakes where carbon has diffused, causing localized melting and surface hardness of 850 Hv can be achieved.

G Ricciardi et al [33] treated pearlitic grey iron by remelting surface hardening with CO₂ laser and found improved tribological characteristics.

2.4.5.3 Ferritic grey iron

Ferritic grey iron is not readily hardened by laser heating because the carbon is dispersed in graphite flakes, and the diffusion time for transformation to austenite on heating is limited. Rims of martensite and retained austenite form around the flakes, but no matrix hardening occurs. For this reason, attempts to harden GGG 50 have not been successful [9].
2.4.5.4 Austenite grey iron

Austenite grey iron has limited hardenability, since it is designed such that austenite is stable at room temperature. A hardness of about 530 Hv is typical.

2.4.5.5 Nodular iron

Graphite is present in nodular iron in the form of discrete spheroids, in the matrix of pearlite, ferrite or a mixture of these. In contrast to the continuous conducting lamellae found in grey iron, thermal conduction occurs mainly through the matrix in nodular irons. The thermal conductivity of nodular iron is therefore lower than that of grey iron and so a steeper temperature profile is induced during surface heating. In addition, since nodules dissolve more slowly than lamellae, because of the smaller ratio of surface area to volume, relatively long treatment times are required to cause sufficient redistribution of carbon to produce transformation hardening. The result is that the surface is easily reheated and melted. The tolerance on processing parameters is therefore narrower than that for hardening grey iron.

The matrix transforms to austenite on heating. A fine pearlite matrix transforms more readily than a matrix of coarse pearlite or ferrite, in which superheating is observed. Carbon diffuses from the graphite nodules into the surrounding austenite creating a carbon concentration gradient. The timescale for noticeable diffusion is of the order of 1 s. in regions adjacent to the nodule, where the carbon concentration is sufficiently high to lower melting temperature below the local peak temperature, incipient melting at the rims of the nodules occurs. This is most noticeable on the upper surface of a nodule where the peak temperature is higher. On solidification, such regions transform into ledeburite. Further from the nodule surface, where the carbon concentration is sufficient to depress the $M_f$ temperature below room temperature, a rim of retained austenite is observed on cooling. In regions of lower carbon content, even further from the surface, martensite is formed on cooling. Regions of very low carbon content transform to ferrite on cooling. Thus, rims of ledeburite, retained austenite and/or martensite are observed around graphite nodules. The extent of transformation depends on the time available for carbon diffusion and
the temperature at which this occurs and so increases with an increase in beam interaction time and surface temperature.

T Fukuda et al [34] presented the results of the applications of laser transformation hardening spheroidal graphite cast iron by using 1.25 kW CW CO$_2$ laser. They found that, hardening of the cast iron, as compared to medium carbon steel, offered advantages such as lower energy density and lower beam speeds.

2.4.5.6 Pearlitic nodular iron

The hardened microstructure of pearlitic nodular iron comprises nodules in a martensitic matrix, around which a thin rim of ledeburite may be present. Hardness values above 900 Hv have been obtained in iron in both quenched and tempered and normalized conditions, in hardened rim grooves in diesel engine pistons. Hardening to a depth of about 1 mm has been produced in GGG 60. The increased hardness provides an improvement in the resistance to abrasion and plastic deformation.

2.4.5.7 Ferritic nodular iron

Since the carbon content of the matrix is very low and carbon is dispersed in nodules, ferrite nodular iron is not readily hardened by laser heating. Regions containing very low concentrations of carbon transform to ferrite, rather than martensite on cooling. However, the treatment is very slow, which would not be considered economically viable, enables hardness values in the range 400 -500 Hv to be achieved.

2.4.5.8 Ferritic-pearlitic nodular iron

The transformed microstructure of a nodular iron with a matrix of ferrite and pearlite comprises partially dissolved graphite nodules with thin rim of ledeburite (where incipient melting occurs) surrounded by a rim of martensite. Hardness values in the range 800-960 Hv have been obtained accompanied by a ten-fold reduction in wear compared with untreated nodular iron.
Janez Grum et al [35] found that laser remelting can be regarded as a highly successful method for increasing wear resistance and hardness of nodular iron (C=3.64 wt. %). The process of rapid heating above the melting point temperature and the temperature of the austenite transformation creates conditions for the formation of metastable microstructure that can offer important technological properties such as high hardness, good wear and corrosion resistance.

2.4.5.9 Bainitic nodular iron

A bainite matrix, produced by heat-treating a pearlitic nodular iron is particularly suitable for laser hardening. Martensite with hardness in excess of 610 Hv is produced.

2.4.5.10 Malleable iron

Malleable iron may also be hardened by laser heating. However, the low amount of widely dispersed carbide limits the hardness that can be achieved without surface melting. Preferential melting occurs around the temper carbon, producing an irregular surface.

2.4.5.11 Ferritic (black heart) malleable iron

If processing parameters are chosen to allow sufficient time for diffusion of carbon from temper graphite, a martensite structure can be produced by laser heating of Ferritic malleable iron. Hardness values in the range 600-700 Hv are typical.

2.4.5.12 Chromium -molybdenum alloy iron

Cast iron that is alloyed with elements such as chromium and molybdenum to enhance hardenability respond particularly well to transformation hardening. The hardness profile is characterized by an extended flat plateau, which falls sharply to the base material hardness. The hardened zone is thus defined unambiguously and compliance with manufacturing requirements can be established easily. A maximum
hardness of 900 Hv extending to a depth of almost 1.5 mm has been reported in a cast iron alloyed with 0.3% Cr and 0.3% Mo. This represents an increase in hardened depth of about 50% in comparison with unalloyed grey iron.

2.4.6 Non-ferrous materials

2.4.6.1 Zirconium alloys

Alloys of zirconium and niobium are used in pressurized tubing in the power-generation industry. Laser heating of Zr-2.5Nb has been observed to produce martensite transformation, resulting in an increase in hardness from 275 to 350 Hv in a surface layer a depth of 10 μm.

2.4.6.2 Titanium alloys

Improvements in the fatigue life Ti-6Al-4V can be achieved by laser heating, based on the reduced fraction of α in the microstructure, and a reduction in grain size. The heat affected zone below the laser melted region of the (α + β) titanium alloy Ti-10V-2Fe-3Al transforms to β on heating, which partially transforms to orthorhombic martensite (α' ) on cooling.

2.5 Process modeling

The aim of modeling of laser hardening is to describe the heat flow, phase transformation in addition, hardness developed for a range of laser beam processing parameters with variety of ferrous materials. Candidate materials and procedures may thus be shifted rapidly and models can be used to obtain an initial set of processing parameters based on the component hardness and the hardened depth required [9].

Many authors have reported various models. S P Gadag and B S Yilbas has contributed considerably in modeling the process by using different approaches.
2.5.1 Modeling through metallurgical analysis

During laser surface hardening, many phase changes occur. The process time that includes heating and quenching material substrate is very short. Correlating the resulted microstructure with theoretical temperature profile calculations, many attempts have been carried out to understand the effect of process parameters and to model the process. Some of the attempts in this direction are described as below.

J Senthil Selvan et al [36] carried out investigations on En 18 steel with 1300 & 1500 W CW CO$_2$ laser. The power density and travel speed used were 130 to 150 W/mm$^2$ and 1 m/min along with surface coating of MoS$_2$. The phase transformations occurring were studied using optical microscope and scanning electron microscopic analysis. The microstructural behavior is correlated by theoretical temperature profile calculations. From this study, it was observed that laser surface hardening produces wear resistant and highly hardened layer consisting of metastable martensite and carbides. Hence, the laser surface hardening technique can be used in the automobile industries to increase service life of camshafts and crankshafts made of En 18 steels.

Tamas Reti et al [37] developed a new phenomenological model for predicting the hardness distribution after rapid austenization and quenching resulting from short cycle heat treatment such as laser hardening of steels. The applicability of this new approach is demonstrated by computer simulation and experiments with a laser hardened low alloy hypoeutectoid steel.

K Obergfell et al [38] carried out experiments in laser hardening with three different steels with C content of ~0.2 wt. % and different contents of chromium and vanadium. The laser-affected zones beneath the surface were characterized by microhardness, dislocation density, carbide type size and distribution as well as grain size of austenite.

Kwo-An Chiang et al [39] studied the effect of laser hardening on H13 steel. They studied the phase transformations that occurred by using optical and scanning electronic microscopic analyses, and correlated the microstructure behavior by calculating the theoretical temperature profile. The laser treatment performed using a 2 kW CW CO$_2$ laser. The laser power and travel speed used were 150 -250 W and 10-25 mm/s respectively. The oxide-free coating and the nitrogen gas was used during
experimentation. They observed several significant changes in the microstructure. The melt layer was surrounded by an extremely fine lamellar structure and the hardened layer was characterized by martensite within the metallic carbides precipitated at the grain boundary. In the heat-affected layer, the metallic carbide particles became larger and many more were formed because of tempering.

G N Haidemenopoulos [40] simulated moving boundary diffusion problem for rapid austenization during laser transformation hardening of hypoeutectoid steel. The calculations were performed by applying the coupled thermodynamic and kinetic approach. It is found that it is possible to simulate the microstructural evolution under rapid thermal cycles. Therefore, it is possible to predict quantitatively the effects of heating or cooling rates as well as dwell time on the microstructural features, which controls properties. The direct link between process parameters and properties show that these simulations can be a powerful tool for alloy design and process optimization.

S P Gadag et al [41] carried a critical assessment of laser surface treatment of structural sensitive, hypereutectic ductile iron by CW CO$_2$ and pulse Nd: YAG laser. The process of laser melting has been numerically simulated by 3D FDM program and experimentally verified. Onset of solid transformation, superficial or complete melting derived from numerical and experimental methods, has also been investigated. Melt and transformation profiles influenced by processing parameters, macro and microhardness, dry sliding wear and friction, corrosion and cavitations erosion in de-ionized water, synthetic sea water or mild acid, have been calculated. This provides better understanding of properties of laser surface modified ductile iron and its processing. The improved surface properties of laser processed ductile iron have been wide spread application for marine and automotive components - crankshafts, cam lobes, cylinder liners etc. Ductile iron with Bull’s eye pearlitic matrix was surface treated by 300 W and a 5 kW CO$_2$ laser. Pulsed Nd: YAG laser has been successfully applied in laser surface treatment of ductile iron and compared with CW CO$_2$ laser.
2.5.2 Modeling the temperature fields

2.5.2.1 Empirical relationships

Empirical relationships have been developed from extensive experimental trials to describe the effect of processing parameters on the geometry of heat flow and hence the geometry of hardened region obtained by assuming that the extent of the depth of hardened region corresponds to a particular isotherms [9].

L J Yang et al [42] established correlation between laser power \((P)\), beam diameter \((D_b)\) and traverse speed \((v)\) and the depth \((D_p)\) and width of hardened zone \((w)\). It has been found that the case depth is not significantly by beam diameter. However, the beam diameter affects the gradient plot of \(\frac{P}{(D_b v)^{\frac{1}{2}}}\) against \(D_p\) as explained by Courtey and Steen. They proposed a new empirical equation for the case depth as below

\[
D_p = 0.95 \frac{P}{v^{\frac{1}{2}}}
\]

An empirical equation for predicting width of known geometry of parabola is given as

\[
w^2 = (0.85 + 1.04D_b) \frac{P}{v^{\frac{1}{2}}}
\]

The specimen used during experimentation was DF-2 tool steel and 1kW axial flow CO\(_2\) laser.

H M Shang [43] reexamined the empirical equation proposed by L J Yang et al. by using existing closed form solutions for some heat conduction problems. In spite of their limitations and over simplifications, these solutions offer satisfactory explanation of the experimental data.
2.5.2.2 Analytical solutions

Analytical solutions for the temperature fields can be obtained by making a number of assumptions about the heat source and the material. The laser beam can be considered a well-defined heat source. The material can be considered to behave as a semi-infinite body, with material properties that do not vary with direction or temperature. Heat flow may be considered to be steady state i.e. the isotherms surrounding the heat source appear stationary to a located at the heat source. Solutions for temperature fields around moving point, disc and rectangular heat sources yield an equation for the thermal cycles in the material. Expressions for peak temperature, heating and cooling rates and thermal dwell times can then be obtained, which indicate that heating rates between $10^3$ and $10^4$ Ks$^{-1}$ and thermal cycles of duration $< 1$ s common during transformation hardening. Simplified solutions may be obtained by assuming that the depth of the transformed region is related to the surface temperature. Analytical solutions yield explicit relationships between process variables and temperature fields and provide a reliable basis for models of solid-state structural transformations [9].

There is a good number of published literature on laser hardening process analyzing thermal and metallurgical effects in the work-piece where phase transformation occurs during the process of heating followed by cooling. Knowledge of the temperature profile provides the prediction of the heat-affected zone, phase composition and hardened layer depth. In order to describe the temperature profile, heat transfer models and mathematical expressions have been developed [60]. The analytical solutions give more accurate predictions that are closer to practice. They also provide a better insight into physical process of laser hardening [53].

Modeling of the heating process minimizes the experimental cost, provides optimization of affecting parameters, and improves the understanding of physical process involved in the laser work-piece interaction. Considerable research studies were carried to explore heating process [59].

In recent years, there has been a significant amount of work done on the modeling of laser/material interaction and industrial heat treatment applications, yet this is still a comparatively young science and models are relatively incomplete.
Considerable work has been done in the area of modeling transformation hardening of materials by a CO$_2$ laser, which will aid in the development of models for transformation by Nd: YAG lasers.

Because transformation hardening is dominantly a heat transfer process, models have justifiably concentrated on calculating temperature distributions. Many solutions to the one-, two-, and three-dimensional heat conduction equations have been published in relation to modeling of laser heat treatment. Some of the earliest work was with regard to obtaining analytical solutions to the one-dimensional heat conduction equation. Later work has both analytical and numerical techniques to achieve a set of temperature distribution, which can be used to calculate hardening parameters. In the past, laser surface treatment has relied on a beam scanning across the surface of a work-piece. Because of this, models typically assume there is some beam velocity across the work-piece and obtain quasi-steady state solutions [51].

Selichiro Kimura et al [44] carried out the study concerned with laser transformation hardening through heat conduction theory. The simplified equations were derived by introducing some dimensionless groups to predict the surface temperature of the material and the transformation-hardened depth as a function of the parameter to be irradiated on, which closely agreed with experimental results carried with CO$_2$ laser for the carbon tool steel.

In the application of pulsed laser heating, such as laser hardening of metallic surfaces, conduction limited process is dominant mechanism during the laser-workpiece interaction. Consequently, time unsteady analysis of this problem becomes necessary. B S Yilbis [45] examined the time unsteady analysis of the conduction limited process for a time dependent laser power intensity. An analytical solution to the problem is obtained with appropriate boundary conditions. It is found that

i) The time at which the maximum temperature occurs is a function of pulse parameters and not of material properties. The material properties only becomes important as the pulse length reduces to Q-switch i.e., $t \sim 10^{-9}$ s.

ii) A phase lag occurs between the position of the maximum temperature and maximum pulse intensity. The phase lag may be varied by changing the shape of the pulse.
iii) The maximum temperature at the surface does not depend on the absorption depth knowing that the surface temperature only depends on the absorption depth in the initial stages of the pulse. Consequently, the maximum surface temperature is independent of wavelength of the laser.

iv) If the pulse decays slowly, the time at which the maximum temperature occurs is very much greater than the pulses rise time.

v) The frequency of repetitive pulsing at which the material appears to integrate thermally depends on the pulse shape. The condition in which the thermal integration to occur requires a minimum pulse rate of 100 Hz.

G Ricciardi et al [46] developed a one-dimensional mathematical model, which describes the thermal field versus time depth in a very general way. To obtain the equation which gives the temperature pattern at various depths and as a function of time, the Fourier law of heat conduction was used at the starting point. With some simplifying hypotheses, it takes the following form

\[ k \frac{\partial^2 T}{\partial z^2} + A = C_p \rho \frac{\partial T}{\partial t} \]

This equation gives solutions, which vary depending on whether the work piece being examined can be considered as a semi-infinite or of infinite thickness, and it can be obtained using the following hypothesis:

- constant heat parameters of the material and coefficient of absorption
- initial temperature of the work piece 0°C
- negligible phase changes
- constant material density
- homogenous and isentropic material
- uniform distribution of laser energy
- mono-dimensional flow
- no irradiation or heat exchange with exterior.
After normalization, by means of boundary conditions modifications and some simplifications, the following expression is produced:

\[
T(z, t) = \frac{F_o D}{k} \text{erfc}(\sqrt{\frac{z}{D}}) + \frac{F_o D}{k} \sum_{n=1}^{\infty} \left[ \text{erfc}\left(\frac{z_n I - z}{D}\right) + \text{erfc}\left(\frac{z_n I + z}{D}\right) \right]
\]

With \( l \) is thickness of the finished sheet in which the first term is the same as that of the semi-infinite thick sheet, whilst the second expressed as infinite and interruptible series at an appropriately selected value, can be interpreted as the contributor to the temperature by the subsequent reflections of heat between the upper and lower face of the workpiece. The model developed validated experimentally.

Camoletto et al. [47] tested the one-dimensional mathematical model developed by G Ricciardi et al [46] for hardening of turbine blades using 15 kW CO\(_2\) laser and found good agreement.

S M Zubair et al [48] discussed an analytical solution of a semi-infinite solid due to a general time-dependent laser source and convective-boundary condition. The heat conduction equation describing the temperature distribution in a semi-infinite, homogenous and isentropic body with an energy source term is given by:

\[
\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + q
\]

The analytical solution for the above one-dimensional equation is found by using Laplace transformation for convective boundary conditions. It is further emphasized to note that the analysis discussed is limited for convective cooling of the exposed material surface; however, radiation losses will be important for most materials approaches phase-change temperatures. Authors have recommended a numerical model for checking analytical solution for the applications in which radiation losses and ablating boundary conditions are important.

Transport and generation of heat is subject of the phenomenon of relaxation, namely a change in temperature gradient does not cause an instantaneous, corresponding change in heat flux and in case of an internal energy whose capacity depends on temperature and a change in temperature is not immediately followed by a corresponding change in source capacity. In most engineering applications the
relaxation stage of thermal process can be neglected. However in highly transient heat
transfer processes, such as laser pulse heating, the relaxation effect plays an important
role.

B S Yilbas et al [49] presented an analytical solution one-dimensional
transient for pulsed laser heating with convective boundary condition. The time
exponentially varying laser pulse is employed in the analysis. A closed form solution
pertinent to, laser time exponentially varying pulse is obtained using a Laplace
transformation method. The heat equation used for getting the solution is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{I \delta}{k} \left( e^{-\nu t} - e^{-\eta} \right) = \frac{1}{\alpha \partial t} \frac{\partial T}{\partial t}$$

H G Woo et al [50] developed a new analytical solution to predict transient
temperature distribution in a finite thickness plate during laser surface hardening. This
analytical solution was obtained by solving a three-dimensional heat conduction
equation with convective boundary conditions at the surface of the work-piece. Three-
dimensional heat conduction equation in Cartesian co-ordinate system is given as:

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) T$$

The temperature distribution owing to a traveling distributed heat source is
formulated by the use of Green's function. The solution is obtained by integrating the
product of Green's function and heat distribution over the surface of interest and
subsequently integrating them with respect to time in moving coordinate system.

Absorptivity were measured experimentally under various hardening
conditions, including variation in coating thickness, laser beam power and beam travel
velocity to calculate the temperature field numerically. Comparison of theoretical and
experimental results found good agreement.

Paul R Woodard et al [51] developed a new approach, uses discrete pulses to
create a series of hardened "spots". An analytical solution to the axis symmetric heat
conduction under a Gaussian energy distribution is developed which can be used to
calculate the temperature distribution from a short laser pulse. This method is also
used to calculate the size of transformation hardened spot under the incident energy of stationary laser.

The transient heat conduction for cylindrically symmetric flow with no internal energy is given by:

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \rho C_v \frac{\partial T}{\partial t} \]

For the case of constant, isentropic properties, this equation reduces to

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \]

By using Lambert's law and taking sequentially the Hankel and Laplace transformations the temperature in integral form is obtained which provides the required temperature distribution by using Bessel function. Comparisons were made to the finite element method, showing excellent agreement.

R. Festa et al [52] gives a straightforward procedure for predicting the hardened depth and its maximum achievable values for simple geometries and no surface melting. Two thermal models are considered: the 2-D solution for a uniform strip heat source moving on the surface of a semi-infinite solid and 1-D solution for uniform heat flux on a semi-infinite body given by Carslaw and Jaeger (1959). Conditions for which those of the latter approximate the results by the former model are given. For both models, dimensionless correlations, approximating the analytical expressions, are presented and experimentally validated.

R Komanduri et al [53] developed an analytical solution for the temperature rise distribution in laser surface transformation hardening of a steel work-piece of finite width based on Jaeger's classical moving heat source method and Carslaw and Jaeger to predict the optimal operational parameters. The laser beam is considered as a moving plane disc heat source with a pseudo-Gaussian distribution of heat intensity. It is general solution in that applicable for both transient and quasi-steady state conditions. The effect from two boundaries of the work-piece of finite width is included in the analysis. The solution can be used to determine the temperature rise distribution in and around the laser beam heat source on the work surface as well as
with respect to depth at all points including those are very close to heat source. The width and depth of the melt pool and the hardening zone near the surface of the work-piece with finite width can also be used calculated under transient and quasi-steady state.

In a number of articles concerning the problem of the treatment of mathematical modeling of materials by concentrated energy flows, mainly pulsed or continuous conditions are considered, whereas only in some articles are the peculiarities of pulse-periodic action analyzed. This derives the difficulties in the simultaneous description of heating/cooling and evaporation phenomena. Usually either heat transfer during pulse-periodic energy flow action is analyzed or only the movement of melting front, in one direction i.e. in the absence of solidification. The authors reported the relationship between the structure (i.e. pulse duration, duty cycle, value of energy density flow etc.) of energy density flow and evolution of heat processes. The proposed one-dimensional transient model includes the process of heating, melting evaporation and solidification under the action of an energy flow with different shapes on a metal slab are considered and melting (solidification) is determined by the classical Stephan boundary condition.

The results of mathematical modeling show the necessity of considering the movement of two-phase boundaries, melting (solidification) and evaporation fronts. Yu Smuror et al [54] reported the numerical analysis and showed the possibility to determine number of regularities in heat processes of the pulse-periodic energy flow action.

Da Yu Tzou et al [55] presented the temperature distribution around a fast-moving heat source with a finite dimension has been obtained by integrating Green's function in the thermal wave theory. All the thermal properties have been assumed constant in the analysis. When thermal conductivity becomes strongly dependent on the temperature gradient then the Green's function governing thermal waves emanating from a point heat source used becomes non-linear and requires major modifications.

O O Diniz Neto et al [56] solved the non-linear parabolic differential equation for heat diffusion equation to study the transient behavior of temperature distribution.
in a solid heated by short powerful laser pulses. It was based on a three-dimensional model of laser heating problem in which the temperature-dependent coupling between the laser pulse and the sample, and the temperature-dependent characteristics of the sample are fully accounted for. The equation in polar coordinate was as below:

\[
\frac{1}{k(T)} \frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \theta}{\partial r} \right) + \frac{\partial^2 \theta}{\partial z^2} + \frac{A(r, \tau, T)}{k_o}
\]

There is no analytical solution to above equation subjected to the boundary conditions considered. Thus, the solution to the equation is through a numerical scheme based on a finite difference formulation that explores the successive over-relaxation iteration procedure. The numerical results were presented and discussed from the point of view of an application of the metals heated with a pulsed Nd: YAG laser.

L Malinowski [57] solved the relaxation equation of heat conduction and generation by method of Laplace transforms for the case of a semi-infinite body and an arbitrary dependence of surface temperature on time. For the case of equality of the relaxation time of the heat flux and the relaxation time of the internal heat source capacity the Laplace domain solution is inverted analytically, otherwise numerically. Exemplary calculations are carried out for the surface temperature function in the form of a rectangular pulse. The results shows the significant differences can occur between relaxation and parabolic models in quantative and qualitative terms, which do not disappear for long times.

Ali A Rostami et al [58] studied the rapid melting and solidification of material. The enthalpy technique was used in an explicit difference form to calculate the location of solid-liquid interface and the temperature distribution in the target. The technique was modified so that it is not necessary that the temperature of the mesh containing the interface remain constant at the melting point. The method was applied to the problem of rapid melting and solidification of a substance resulting from the application of a pulsed laser beam. The temperature plateau which usually results when the enthalpy method is used was eliminated by using energy boundary condition at the solid-liquid interface. Good agreement was obtained between predictions and experimental data for the melt depth profile in an aluminum target.
2.5.2.3 Numerical solutions

The heat flow geometry may also be solved numerically by integration and finite difference methods, to give temperature fields around both moving and stationary surface heat sources, with various geometries and power distributions. Such solutions are flexible and can take into account variations of material properties with temperature but they may require considerable computing power and time for execution [9].

Noël Cheung et al [60] reported a mathematical two-dimensional transient model to predict the depth of laser heat treated zone in the laser transformation process. The phenomenological description of this process is given by the Fourier equation, which describes the way in which the absorbed energy is transmitted throughout the irradiated material. The Fourier equation of heat conduction was solved by using the Finite Difference Method in cylindrical coordinates in order to study the temperature distribution produced in a work-piece and hence obtain the depth to which hardening occurs by analyzing the cooling rates according to the continuous cooling diagram. The theoretical simulations are compared with results produced experimentally by a CO$_2$ laser operating in continuous wave, showing good agreement.

B S Yilbas [61] modeled laser short pulse heating with convective boundary conditions. Electron kinetic theory and the Fourier heating model are taken into account when modeling process. The governing equations are nondimensionalized and the numerical method employing a finite difference scheme is introduced for solving governing equations. The range of Biot number values is considered to account for convective loss from the surface during the heating process. The electron kinetic theory predictions at high Biot numbers approach the Fourier heating model findings as the heating progresses.

Bekir S Yilbas [62] also presented a numerical solution for a pulsed CO$_2$ laser heating process, including heating, melting and evaporation. Completely analytic solutions to the Fourier equation are possible with conduction-limited heat transfer, but impossible with the evaporation-controlled process. In the present study, a one-dimensional solution of the laser heating problem is considered for metals, since the
incident laser beam is focused onto the metal surface, resulting in a Gaussian profile, and the central region of this profile is fairly constant. Consequently, a one-dimensional solution of Fourier equation may be considered as sufficient to describe the energy transfer process. A finite difference approximation is employed to solve the heat transfer equation. In this analysis, the repetitive laser pulse heating process is considered and thermo-physical and optical properties are considered as temperature dependent.

S P Gadag et al [63] reported simulation, modeling and thermal analysis of laser processing as a three-dimensional (Cartesian coordinate) quasi-steady moving heat source problem by a Finite Difference Method, considering temperature dependent energy absorptivity of the material to laser radiation, thermal and physical properties \( (k, \rho, C_p) \) and freezing under non-equilibrium conditions employing Scheil’s equation. This includes assessment of the peak temperature attained at the surface, temperature gradients, the freezing time and rates as well as the geometric profile of the melted, transformed or heat-affected zone. Computed geometric profiles or depths are in close agreement with experimental data, validating the numerical scheme.

M Labudovic et al [64] presented a three-dimensional finite element modeling of a laser surface modification. The design capabilities of the ANSYS parametric design language (APDL) were employed for this purpose. The model calculates transient temperature profiles and dimensions of fusion and heat-affected zone (HAZ). Model simulations were compared with experimental results and found good agreement. The transient temperature distribution \( T(x, y, z, t) \) satisfies the following differential equation for three-dimensional heat conduction is used

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \rho c \left( \frac{\partial T}{\partial t} - v \frac{\partial T}{\partial x} \right) = Q
\]

Adam Bokota et al [65] presented a laser hardening simulation model coupling of thermal field and phase transformation. The thermal field distribution was determined based on the Fourier-Kirchhoff equation with the convective term, the solution of which was obtained by integrating Green's function over the considered region. The fractions of phase created during the phase transformations were
calculated by use of a TTT-heating diagram and TTT-cooling diagram. The coupled effects of temperature field and phase transformations were considered by applying the additivity principle and Avrami formulae for diffusion transformations while the Koistinen and Marburger empirical formula was used to calculate the martensite transformation. The numerical calculations were made for a steel rectangular bar hardening by the laser method.

S Z Shuja et al [66] conducted the study to simulate three-dimensional laser heating of steel substrate when subjected to impinging gas. The transient Fourier heat conduction is considered to compute the temperature profiles in the solid substrate. A numerical method using control volume approach is introduced to solve governing flow and energy equations. The study is extended to include four gas jet velocities. It is found that impinging gas jet velocity has a considerable effect on the resulting gas side temperature. Moreover, as the radial distance from the heated spot center increases, the temperature at the surface decreases rapidly. In addition, the temperature profiles inside the solid substrate are not influenced considerably by assisting gas jet velocity.

B Q Xu et al [67] got the transient temperature fields generated by a pulsed laser in aluminum/methyl-methacrylate system and aluminum/copper systems are obtained by using finite element method. The spatial mode of the laser beam is assumed as Gauss distribution so that a cylindrical coordinate system is adopted.

2.6 Scope of the present work

Based on the outcome of the literature survey, the objectives and scope of the present work are set forth as below.

- An analytical approach to heat flow, although elegant and intuitive as its results may be, is unable to impose proper initial and boundary conditions. Therefore the development of two-dimensional model with the most realistic initial and boundary conditions is considered.

- No report could be found for the laser hardening of cast iron using Nd: YAG laser, therefore experiments are planned to explore the process. An attempt is
planned to develop the technical know-how for laser hardening of diesel engine cylinder (Cast Iron) through

i. experimentation for optimization

ii. experimentation for overlapping

iii. study of improvement of wear characteristics and

iv. validating the developed model.