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Surface treatment of cast iron by adding different alloying elements to form metallic glass structure layer using an industrial carbon dioxide laser

Mohammad Riahi
University of Northern Iowa

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industrial carbon dioxide laser**

Riahi, Mohammad, D.I.T.

University of Northern Iowa, 1991

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Ann Arbor, MI 48106**

SURFACE TREATMENT OF CAST IRON
BY ADDING DIFFERENT ALLOYING ELEMENTS
TO FORM METALLIC GLASS STRUCTURE LAYER
USING AN INDUSTRIAL CARBON DIOXIDE LASER

A

Dissertation

Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Industrial Technology

Approved:

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August 1991

DEDICATION

This dissertation is dedicated to Hadhrat Fatematol-Zahra, daughter of the holy prophet of Islam, Mohammad (may peace and blessing of God be upon him) and all her children, from Hussein to Ruhullah.

تقدیم به پیشگاه مبارک حضرت زهرا الطهر، سیده نساء العالمین سلام الله علیها :
 امید عاجزان دارم که این هدیه ناقابل مورد قبول حضرتش و فرزندانش
 بآرامش، از حسین تا روح الله علیه السلام قرار گیرد و اسباب شفاعتی
 بسببش در این حقیر عاصی در روز محشر.

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Approved:

Faculty Advisor

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ABSTRACT

Wear and corrosion are the two factors that make utilization of metals very costly. Extraordinary amount of time and money is spent to replace metallic parts affected by either wear or corrosion. Cast iron that is used very widely in a host of different industrial products is one such metal. Among the various methods used to improve the properties of metals, production of amorphous metals is highly noticeable. This process is done by treating the base metal in a certain technique which produces a metal that is more resistant to wear and corrosion.

This study was conducted to examine the prospect of forming a metallic glass layer on the surface of gray cast iron by adding boron, silicon and cobalt; coupled with the utilization of an industrial carbon dioxide (CO_2) laser. Three different mixing ratios of the aforementioned alloying elements as well as four different groove sizes on the surfaces of the samples were used.

Determination of the characteristics of the laser-formed layers on the surfaces of the samples were conducted by the utilization of x-ray diffraction techniques, mechanical testing, Rockwell hardness testing method, as well as metallographic examinations.

The collected test results led to the conclusion that the formation of amorphous metal on the surface of gray cast iron is possible and practical when certain percentage of

mixing ratios of boron, silicon and cobalt are used and lased by a 1300 watts industrial CO₂ laser. Furthermore, the hardness results indicated that a considerably higher degree of hardness resistivity, up to 70 HRC is achievable on the surface of a gray cast iron that has a hardness resistivity of 32 HRC. The micrographical analysis of the formed layers showed textures of a super-saturated structure that presented a high degree of resistivity to both wear as well as corrosion.

Boron content attributed to achieving of a high degree of hardness. Particularly when mixed with cobalt and silicon, in the ratio of up to 40% boron content, improved the hardness number directly. Beyond the 40% ratio, the effect of boron on the hardness improvement was not very significant. Three geometrically shaped grooves were machined on the surface of each specimen. Each shape was machined in four different depths on four different specimens. The depth of the lased areas ranged from 0.45mm to 2.15mm.

CHAPTER 1

INTRODUCTION

Metals have played a major role in the development of civilization. The most widely used metal in terms of both weight as well as volume has been iron. The earliest known appearance of iron according to Pollack (1988) goes back to the time of building of the great pyramids of Egypt, approximately 5000 years ago. Old Chinese and Indian civilizations used iron also. Out of several applications of iron, tool-making appears to have dominated the trend. Palestinians were known to have first developed tools made from iron back in about 1200 B.C. where iron was referred to as "star metal" and the knowledge of smelting appeared to have emerged (Pollack, 1988).

Cast iron is produced in six varieties for commercial use. Pig iron, gray iron, white iron, chilled iron, malleable, and nodular iron. Gray cast iron is the cheapest to produce and offers great wear resistance. The two aforementioned characteristics of gray cast iron have made it the most practical and advantageous metal to be used by a host of industries and in many manufacturing processes. Engine blocks, heads, pistons, clutch plates, and similar parts as well as guard rails, machine bases, valve housings, and lightly loaded gears are but to name a few of the gray cast iron's applications (Orthwein 1990).

In order to produce a higher resistivity with regard to wear in cast iron, several different methods have been adopted by the iron producers. Categorically these methods are referred to as hardening. Normalizing, annealing, or austenitizing at different temperatures and finally, quenching are the most common methods of hardening (American Society for Metals, 1988). There are certain applications however, in which surface hardening of cast iron is sought. For this purpose, direct heating by either flame or induction have been practiced exclusively.

Numerous difficulties are associated with the process of surface hardening. Excessive cost and time, involved in conducting of the surface hardening coupled with the deficiency in precise and homogeneous treatment of the surface of cast iron has caused researchers to start pursuing investigation into other viable alternatives. In conjunction with the physical treatment (thermal) of the surface, chemical compounds of different natures have also been used for the protection of cast iron's surface in certain applications.

Among the various efforts on the improvement of cast iron's surface characteristics, utilization of industrial CO₂ Laser in conjunction with the addition of other substrates has a great potential for solving the

aforementioned problems associated with the surface treatment. The history of this method is fairly recent and has been practiced since 1981. Successful experiments of this surface treatment method were conducted by Schaefer, Boettinger, and Biancaniello (1981), Ayers (1981), Mukherjee, Kim, and Walter (1981), Fahmy and Tabrizi (1988), and Fahmy and Helzer (1988). Their findings suggested that continuation of these research efforts have great potential in producing a very desired outcome in the surface characteristics of cast iron surface after being lased in conjunction with the addition of other elements.

The development of light amplification by stimulated emission of radiation (LASER) technology was based on the theory that particles of light with energy of a particular frequency could stimulate atomic electrons to emit radiant energy as light of that same frequency. This theory was adopted to invent a machine capable of generating that radiation. This machine is called LASER (Letokhov & Ustinov, 1983). One case is carbon dioxide laser which is used commonly in a variety of capacities and applications. Recognized for its practicality and versatility in the metal industry, a CO₂ laser is readily available in different power ranges. Furthermore, a CO₂ laser is relatively more affordable and economical to use in comparison with the conventional machinery capable of performing similar tasks. Among the primary applications of the industrial CO₂ Laser

are metal cutting and metal welding. However, according to Hecht and Teresi (1982), it was not until the early 1970s that the laser was used for heat treating of metal surfaces.

There are several different methods of conventional heat treating that each of which is capable of producing a desired degree of crystalline phase transformation in a metal due to their design configurations. Some methods however, would not yield the desired transformations on their surfaces if subjected to different conventional heat treating methods such as tempering, martempering, austempering, annealing and normalizing (American Society for Metals, 1988).

Conventional heat treatment of metallic surfaces are a common practice in regular applications. There are however certain cases in which extra ordinary characteristics are desired of the treated surfaces. One such case is the manipulation of the transformation of the phases on metallic surfaces with respect to time and temperature. Where rapidity in heating and cooling of the treated metallic surface is sought, conventional methods of heat treating could only be extended by a limited amount to reach the desired outcome. Utilization of industrial CO₂ laser for the surface treatment of metals is advantageous in many aspects. Some of the prevailing characteristics of this method are as follows:

1. It does not exert mechanical stress on the workpiece. Therefore a simple fixturing is needed.
2. It has a much lighter weight in comparison with similar mechanical equipments therefore it is more convenient to move around the part while being treated.
3. It can be adapted to different tasks very easily by changing the focusing system and the related energy density at the target.
4. In comparison with the conventional methods, no distortion takes place.
5. Only selected areas or spots on a part would be treated and the remainder of the surface of the part would remain intact.
6. Because less energy is required, heat losses and the time involved is considerably reduced, consequently cost savings would be increased.

Statement of the Problem

The problem of this study was to determine the feasibility and potential surface treating of ferrous base metals by adding multi-substrates and utilizing an industrial carbon dioxide (CO₂) laser to develop a corrosion-wear resistant surface. The following were the variables associated with this investigation. Independent variables were: mixing ratios of the alloying elements, depths of grooves, and geometrical shapes of grooves.

Dependent variables of the study were: structural and microstructural textures, and hardness numbers of the lased areas.

Purpose of the Study

The main purpose of this investigation was to primarily explore and study the possibility of forming a new amorphous layer on the surface of ferrous metals. Particularly utilization of alloying elements such as cobalt, silicon, and boron and using a 1300 watt industrial carbon dioxide laser was targeted.

The secondary purpose of this investigation was to study the microstructures formed by different volume ratios of substrates. Parameters involved were different depths and angular shapes of the grooves on the surfaces of gray cast iron. Microstructural analysis, mechanical hardness and composition of the formed layers were also studied for each groove.

Significance of the Problem

Gray ductile iron castings are perhaps the most widely used products in industrialized settings nowadays. The majority of the castings used are fabricated and then assembled as parts and components of machinery and products of multicomponent at a later time. Once installed, a part

made from cast iron will most likely be affected by wear and corrosion factors that will affect its service life span. Wear is directly linked to use and, apart from exceptional cases, its depth and the degree of intensity could be anticipated based on the application and location. Although proper maintenance would increase the durability of a cast iron product, there are a variety of cases where yet stronger resistance to wear is desired in an iron, e.g. tool and drilling products. Increasing the durability of iron products could bring about an enormous amount of savings in both time and money.

Corrosion on the other hand is not very predictable. It is defined by Uhlig and Revie (1985 p. 12) as "the destructive attack of a metal by chemical or electrochemical reaction with its environment." According to Uhlig and Revie (1985), a new method in corrosion protection of metals could bring about improvements in three significant areas. The first area of improvement would be economic: that which is caused by direct and indirect losses. The direct losses include the costs involved in replacing corroded parts in machinery and structures and their components. De-icing salt applications to bridges and roads in the United States have been estimated to cost \$2 billion for repair or replacement of parts in motor vehicles and \$.5 billion in repair of roads and bridges. Furthermore, there is an extraordinary cost associated with tooling loss costs.

Although exact calculations of monetary losses due to tooling does not seem to be conceivable for all the involved industries and functions, there is a clear indication as to how heavily it can impact the overall cost of production of goods in general. One such case is the replacement of a corroded tube in an oil refinery which by itself does not cost more than a few hundred dollars. However, production loss may cost \$2000 per hour. Another case is the example of a large power plant that could cost in excess of \$50,000 per day for purchasing of power from interconnected electric output. In all, losses of tooling costs alone costs electrical utilities in the United States tens of millions of dollars each year (Uhlig & Revie, 1985). The total combined losses due to corrosion are conservatively estimated to be \$70 billion or 4.2% of the gross national product each year in the United States (Uhlig & Revie, 1985), and \$2 billion in Australia and exceeding \$2.2 billion in the United Kingdom. In each country, the costs associated with direct losses to corrosion were approximately 3-4% of the GNP (Donovan, 1986). Indirect losses cannot be assessed as easily as direct losses. Billions of dollars of loss could be attributed to the indirect impact of corrosion (Donovan, 1986).

The second area of improvement is the safety of operating equipment. Examples of such equipment that require more safety requirements are vessels, boilers,

metallic containers for toxic materials, turbine blades and rotors, bridges, airplane components, and automotive steering components (Uhlig & Revie, 1985).

The third area is conservation. Although, a vast number of iron-ore mines are in operation and the quantity of available ore is great; however, the resources available are limited, and unless a method to conserve iron is discovered, the world will be left without iron sooner than expected (Donovan, 1986).

Research Questions

This study was carried out to discover answers to the following questions:

1. How feasible was the forming of an amorphous metallic layer using [silicon, cobalt, and boron] as substrates on the surface of gray cast iron by utilizing an industrial carbon-dioxide laser?
2. What effects would result from adding silicon, cobalt, and boron in the percentages of 30%, 30%, and 40%, on the mechanical and bonding properties of the treated surface?
3. What effects would result from adding silicon, cobalt, and boron in the percentages of 25%, 25%, and 50%, on the mechanical and bonding properties of the treated surface?

4. What effects would result from adding silicon, cobalt, and boron in the percentages of 40%, 40%, and 20%, on the mechanical and bonding properties of the treated surface?

5. What depth would the formed layer have throughout the laser treated zone?

6. What effects would the formed layer have on the base metal and how well will it adhere to the base surface? Geometrical shapes of the grooves would be in semi-circle, 45 degrees, and 90 degrees angle cut

7. Based on the existing standards and testing methods, what would be the microstructural analyses and the hardness of the formed layer?

Assumptions

This study was predicated on the following assumptions:

1. All of the base samples used had similar compositions.

2. There was no loss of mass of the substrates during the process.

3. A certain percentage ratio of the substrates used already existed in the base samples prior to treatment.

Limitations

This investigation was limited by the following factors:

1. Only gray cast iron was used as the base ferrous metal.
2. Boron, cobalt, and silicon were the only alloying elements used in this study.
3. A typical conventional method such as spectroscopic microstructural analyses was used to observe the formed layer.
4. This study was limited in extent to the available financial assistance provided by the department.

Definitions of Terms

The following terms have been used frequently throughout this dissertation. The definitions of the following terms were taken from the ASM metals reference book 1981 (pp. 1-115):

Alloy: A substance having metallic properties and being composed of two or more chemical elements of which at least one is a metal.

Amorphous: Not having a long range crystal structure; noncrystalline.

Annealing: A generic term denoting a treatment, consisting of heating to and holding at a suitable temperature for a predetermined period of time followed by

cooling at a suitable rate, used primarily to soften metallic materials and alloys.

Austenitizing: Forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing).

Corrosion: The deterioration of a metal by chemical or electrochemical reaction with its environment.

Distortion: Any deviation from an original size, shape or contour that occurs because of the application of thermal stress or the release of residual stress.

Heat Treatment: Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties.

Microstructure: The structure of metals as revealed by microscopic examination of the etched surface of a polished specimen.

Normalizing: Heating ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.

Quenching: Rapid cooling: When applicable, the following more specific terms should be used: direct quenching, fog quenching, hot quenching, interrupted quenching, selective quenching, spray quenching and time quenching.

Substrate: Layer of metal underlying a coating, regardless of whether or not the layer is base metal.

Surface Hardening: A generic term covering several processes applicable to a suitable ferrous alloy that produces, by quench hardening only, a surface layer that is harder or more wear resistant than the core.

Vapor Deposition or Plating: Deposition of a metal or compound on a heated surface by reduction or decomposition of a volatile compound at a temperature below the melting points of the deposit and the base material.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Amorphous metals were defined by Luborsky (1983, p. 1) as "the category of metals that contain no long range atomic order." This characteristic enables amorphous metals to be extraordinary hard and achieve a tensile strength that is extremely high when compared to other class of metals in its range. According to Luborsky (1983), manufacturing of certain amorphous metals with specific alloys, produces a product that would have zero coefficient of thermal expansion. Furthermore, corrosion resistivity is extremely high in amorphous metals and electrical resistivity is in the vicinity of one fourth that of conventional iron or iron-nickle alloys.

Numerous techniques have been practiced to produce amorphous metals. The main method used has been rapid solidification of these alloys from the liquid or gas phase. This process due to its rapidity, freezes the atoms at their amorphous liquid configuration (Luborsky, 1983). Another synopsis for amorphous metal is metallic glass (Polk & Giessen, 1983). Although some metallurgists such as Kramer and Brennel (Luborsky, 1983) were known to have produced some "non-chrystalline" (amorphous) metallic alloys in the early decades of the twentieth century. It was not until 1960 that Duwez and his coworkers in California came up with

the practical method of preparing amorphous alloys by "direct quenching from the melt" (Luborsky, 1983 p. 3).

Prior to 1960 and the discovery of Duwez and his colleagues, amorphous metals were being produced by either electro-deposition or vapor-deposition as early as the 1930s (Polk & Giessen, 1983). According to Luborsky (1983, p. 3), Kramer used vapor deposition and Brenner and his coworkers used electrodeposition methods for the production of amorphous metals. However, the produced metals contained "only one broad diffuse peak in the x-ray scattering pattern in the non-magnetic high-phosphorus alloys."

Because of the unpredictability in the properties of amorphous metals, Luborsky (1983, p. 2) described them as "representing a new state of matter." He went on by explaining that "although amorphous solids consist largely of random aggregates of atoms, their densities are only slightly different from the density of the crystalline structure of the same composition." It is for this reason that Polk and Giessen (1983, p. 213) recommended that certain characteristics of amorphous metals have yet to be discovered. They added that "since 1960, a large number of different alloys, have been produced as metallic glasses." Furthermore, they discussed that interest in these materials has caused both scientific and technological communities to have "burgeoned" and many presentations have followed.

Although considering the short period of time that has passed since the discovery of amorphous metals, the materials scientists seem to unanimously agree on the potentials and probability of discovering yet better alloys with more improved properties. Hasegawa (1983, p. 2) explains:

There are a number of techniques by which the alloys can be produced in their glassy (noncrystalline and thermodynamically unstable) state and these give rise to a variety of interesting and useful properties. The potential uses cover a wide spectrum. Many alloys exhibit high strength and good ductility which make them suitable as reinforcing agents. Others exhibit unique magnetic properties, while some are exceptionally resistant to environmental degradation. Some alloys are expected to possess a surface chemistry not previously known.

Rapid Solidification of Metals

The American Society for Metals (1988, p. 109) defines the rapid solidification as: "rapid change in state from liquid to solid on cooling through the melting temperature or melting range." Another description on this term was presented by Duewez (1983, p. 3) as: "to cross the phase boundaries fast enough to totally, or at least partially, prevent the equilibrium reactions from taking place." A very rapid cooling rate of up to 10^6 degrees centigrade per second was attained for thin sections of a formed metallic glass by a process called "Laserglaze™" Snow, Breinan, and Kear, (1983, p. 139). Among the microstructures achieved by this method were amorphous metallic solids, extended solid

solution phases, ultra-fine eutectics, and refined dendritic structures. This process was conducted by two approaches: (a) by replacing the alloying substrate(s) on the part to be glazed before lasing the part, and (b) by adding the alloying substrates(s) as the part's surface was being lased. In both methods an industrial laser was used for heat treating of the surface of the part.

According to Duwez (1983), the most suitable cooling rate for an effective solidification is in the order of 10^4 degrees centigrades per second and higher. In connection with the practical validity of this theory an experiment was conducted by Snow, et al. (1983). The first conclusion drawn was that for a successful outcome, the rate of rapid solidification at 10^4 degrees centigrade per second was essential. Furthermore, it was deduced that in order to achieve homogeneity of the formed surface layer and its depth, the aforementioned cooling rate should exist.

Metallic Glasses

The American Society for Metals (1988, p. 79) has defined metallic glass as: "A noncrystalline metal or alloy, commonly produced by drastic supercooling of a molten alloy, by electrodeposition, or by vapor deposition also called amorphous alloy."

There are a host of advantages in metallic glasses. Compared to similar materials, metallic glasses exhibit

better behavior in regard to wear and corrosion resistivity and consequently, durability is higher. However, the single most important advantage of metallic glasses is the flexibility in the volume content (Luborsky, 1983). Despite all the positive points about metallic glasses, the main discrepancy in their preparation is that not all alloys can be made to solidify in a glassy form; regardless of how rapidly they are cooled from the melt. Figure 1 illustrates the diagram in which this procedure takes place. On the other hand, some materials which solidify as a glass, are processed to convert them into microcrystalline materials to enhance their strength or hardness (Polk & Giessen, 1983). Existing information indicates that only a limited number of alloys are capable of yielding a metallic glass if rapidly solidified. Figure 2 is an illustration about the formation of equilibrium and non-equilibrium phases in the process of glass forming.

Glass was defined as "a supercooled liquid in which the atomic mobility is so low that the liquid strongly resists shear" (Gilman 1983, p. 346). Based on the given definition, he therefore concluded that "in principle, any normal liquid can be converted into a glass; provided it can be cooled fast enough to bypass crystallization." This process is "easy to do" for polymeric liquids, for their viscosity at the liquid phase is enormously high, hence, they are "slow to crystallize" Gilman (1983, p. 346) stated.

Metals, however, do not follow the same pattern according to Gilman (1983). Reason given is that metals once at liquid stage, have a very low viscosity, they therefore, crystallize rather rapidly. In order to overcome this obstacle in converting metals into glasses a quenching rate of extremely high nature is needed. The required rapid quenching rate for this process according to Gilman (1983) is " 10^{10} degrees centigrade or fahrenheit per second for the conversion of pure metals into glasses." It was pointed out however, that for metallic glasses such as those currently produced or sought which contain some degree of impurity, a considerably lower cooling rate of 10^5 to 10^6 degrees centigrade or fahrenheit per second should be sufficient.

Based on the recent research in the conversion of metals into glasses it could be safely deduced that not all alloys are suitable for production of metallic glasses. Dahotre, Wakade, and Mukherjee, (1985), Chande, Ghosh, and Mazumder, (1985), Mukherjee, Dahotre, and Wakade, (1985), Hawks, Walker, Steen, and West, (1985), Fahmy and Tabrizi (1988), Fahmy and Helzer (1988), Ramous (1989), Beurs and Hosson (1989), Staniek and Hornbogen (1989) and a host of other metallurgists conducted series of experiments on the conversion of ferrous base metals into glasses or preparation of metallic glass on the surface of the base metal and their findings were reviewed to assist this study.

Figure 1. Schematic TTT diagram for crystal growth in an undercooled melt, illustrating (a) fast cooling to form a glass, (b) isothermal heat treatment of the glass giving crystallization at time t_x , and (c) slow heating of the glass producing crystallization at T_x .

Note. From "Crystallization" by M. G. Scott, 1983, Amorphous Metallic Alloys (F. E. Luborsky, Ed. p. 144).

Figure 2. Modification of the TTT diagram of Figure 1 to show equilibrium (α) and non-equilibrium (β) phases. (a) During rapid quenching to form a glass crystallization of α must be avoided; (b) heat treatment of the glass generally produces β

Note. From "Crystallization" by M. G. Scott, 1983 Amorphous Metallic Alloys (F. E. Luborsky, Ed. p. 145).

Davies (1983, p. 12) described the importance of readily glass forming (RGF) alloy systems within which "metallic glass formation from the melt occurs readily." The first class to be "discovered and investigated" according to Davies were "the late transition metal-metalloid (TL-M)" type. This class of metals remain the most important technologically, "especially in the case of glasses based on iron, cobalt and nickel for ferromagnetic applications." Versatility in the applied usage of iron in industry which leads to economical gain on one hand coupled with the scientific studies on the practical aspects of converting iron into metallic glass on the other hand were the principal reasons behind the selection of gray cast iron as the main alloy for the purpose of this investigation.

The following is a rather direct and definitive example of the degree of hardness achieved by the formation of metallic glasses. Gilman (1983, p. 346), elaborated on the metallic glasses and their strength in vivid terms:

No other ferrous materials have yield stress as high as those of metallic glasses, although some steels have comparable breaking strengths. For example, the yield stress of $\text{Fe}_{80}\text{B}_{20}$ glass is in excess of 525000 psi (3620 MPa). This is reflected by high hardness (about dph 1100) and good abrasion resistance. Some glasses are even stronger: $\text{Fe}_{75}\text{B}_{25}$ has a hardness of dph 1300, which corresponds to a yield stress of 575000 psi (3960 MPa). The strain hardening that occurs after yielding is quite small, making glasses plastically unstable in tension, although they can sustain large plastic strains in bending, shear, and compression.

Figure 3 shows the liquidus temperature and T_x as a function of composition for the formation of Fe-B, and Figure 4, illustrates the hardness of Fe-B amorphous alloys as a function of the content of boron.

Process of Metallic Glass Formation

As was pointed out in the proceeding sections, the compositions of the metal-metal glass forming is of a eutectic nature and in certain cases, complex crystal structures and intermediate phases with large unit cells have been observed. Suryanarayana (1983, p. 248) indicated that based on high hardness, high thermal stability, high degree of short range order, and "the close correspondence between the densities of amorphous alloys and the corresponding crystalline intermediate compounds," several different models could be found for the development and formation of metallic glasses. Figure 5 shows the relationship between viscosity and temperature and the behavior of metallic melt toward chrystalization. Figure 6 is a graphical illustration of the relationship between enthalpy and specific heat of metallic melt during vitrification and chrystalization. He also made references to three different models that has been adapted for particular reasons in one or more of the characteristics aforementioned. The conclusion made by Suryanarayana (1983)

Figure 3. Liquidus temperature and T_x as a function of composition for Fe-B.

Note. From Amorphous Metallic Alloys (p. 148) by F. E. Luborsky, 1983, Boston: Butterworths.

Figure 4. Hardness of Fe-B amorphous alloy as a function of the content of boron.

Note. From "Strength, Ductility and Toughness" by Kimura, H. and Masumoto, T. 1983 Amorphous Metallic Alloys (F. E. Luborsky, ED. p. 204).

Figure 5. Viscosity (η)-Temperature (T) behavior corresponding to crystallization and vitrification of a metallic melt.

Note. From Amorphous Metallic Alloys (p. 10) by F. E. Luborsky, 1983, Boston: Butterworths.

Figure 6. Temperature dependence of the enthalpy H and Specific heat C_p corresponding to crystallization and vitrification of a metallic melt.

Note. From Amorphous Metallic Alloys (p. 10) by F. E. Luborsky, 1983, Boston: Butterworths.

indicated that although different models based on different needs and behaviors expected from metallic glasses have been brought forward, none so far has been universally adapted and the concept of metallic glass formation has yet to experience one that would be suitable for general applications.

Some of the different methods of formation of metallic glasses are described by Davies (1983, p. 8). Among the morepractical routes that he pointed out: "solidification from the liquid or vapor states, deposition from a chemical solution or an electrolyte and by high-energy ion or neutron-bombardments of crystalline materials." Perhaps the most important stage of the process of metallic glass formation is the cooling rate part. For unless cooling does not take place at a rate fast enough to overcome and avoid the possibility of crystallization, the process will not be complete.

Although a complete non-crystallization is desired in the formation of metallic glasses, however, at least a significant degree of "vitrification" has to take place to qualify the formed material as metallic glass. According to Davies (1983, p. 8), glass formation takes place in some non-metallic materials a great deal easier than the rest. "silicates and organic polymers" are two examples.

A study by Ramous (1989) was conducted and cast iron was employed as the main element for the formation of an

amorphous alloy. Silicon was used as alloying element in addition to carbon and manganese. The noticeable point in that study was the contribution of silicon to the formation of metallic glass at different depths.

Davies (1983, p. 8) has indicated that the "critical cooling rate T_c " is extremely important for the process of glass formation (Figure 7a). In this regard " T_c " is a measure of glass forming ability or (gfa) and "spans a range of at least seven orders of magnitude for metallic alloys." The cooling rate according to Davies corresponds to a range of critical thickness (Figure 7b). Dahotre et al (1985) also conducted an experiment in which silicon and carbon were used as alloying elements in addition to boron. The results indicated that silicon and boron facilitated the process enormously. Similar experiments have been conducted by Fahmy and Tabrizi (1988), Hawks, et al (1983), Das, Dumler, and Mazumder (1985) in which the same procedure has been followed and comparative conclusions drawn from their studies and the similar studies conducted by others were the basis for the designing of this experiment. The results of the aforementioned investigations contributed largely to the adaptation of the different parts of this research, and selection of the procedures and alloying elements were either directly or indirectly due to the outcome and conclusions of their works.

Figure 7. (a) Specific Heat and (b) Viscosity versus Temperature.

Note. From Amorphous Metallic Alloys (p. 41)
by F. E. Luborsky, (1983), Boston: Butterworths.

Utilization of Alloying Elements

Proper alloying elements and their mixing ratios, coupled with their compositions and properties have been sought by the metallurgists since the time of discovery of metallic glasses. Boudreaux (1983, p. 8) noted that "discovering compositions of matter which would permit attainment of the metallic glass state" has been the topic of research at very early stages in the field of amorphous metals. He further explained that a pattern of "extraordinary similarity" was recognized after some samples were routinely examined by x-ray diffraction. In his study, Boudreaux found out that from six metallic glass alloys studied; five demonstrated striking similarities with their structures. The composition of these five were: (a) $\text{Fe}_{80} \text{P}_{13} \text{C}_7$, (b) $\text{Ni}_{80} \text{P}_{20}$, (c) $\text{Fe}_{80} \text{B}_{20}$, (d) $\text{Pd}_{80} \text{Si}_{20}$, and (e) $\text{Cu}_{57} \text{Zr}_{43}$. Boudreaux (1983) indicated that as a result of his comparative studies based on the functions of composition made on alloys from the Fe-B glass system, that "some improvements to the model are clearly required but have not been found to date." He concluded by noting that "the model is emphasizing a particular form of short-range order, while the actual Fe-B alloy system may be a mixture of two forms." Table 1 provides mechanical properties of selected metallic glasses, steel, and silicate glasses.

Table 1

Mechanical Properties of Selected Metallic Glasses,
Steel, and Silicate Glass

	Yield Strength	Fracture Toughness	
Material	10^3 psi (Mpa)	Ksi in K ₁₀	(Mpa m) K ₄₅
Metallic Glasses			
Fe ₄₀ Ni ₄₀ P ₁₄ B ₆	350 (2410)	8.5 (9.3)	37 (41)
Fe ₈₀ B ₁₀ Si ₁₀	350 (2410)	_____	_____
Fe ₈₀ B ₂₀	525 (3620)	11 (12)	42 (46)
Fe ₆₀ Cr ₆ Mo ₆ B ₂₈	650 (4480)	_____	_____
Ni ₆₉ Cr ₆ Fe ₃ B ₁₄ Si ₈	410 (2830)	21(23)	48 (53)
Conventional Steels			
Type 32 (cold worked)	200 (1380)	_____	_____
AISI 4340	240 (1650)	30 (33)	_____
Ausformed 18% Ni	290 (2000)	35 (38)	_____
Tire cord (0.8% C)	400 (2760)	_____	_____
Silicate Glasses			
E-glass	500 (3450)	0.3(0.3)	_____

Note. From "Ferrous Metallic Glasses" by J. J. Gilman, 1983,
Rapid Solidification Technology, (Ashbrook, Ed. p. 348).

There are three categories of important amorphous alloys. The transition metal metalloid (TM-M) alloys, the (RE-TM) or rare earth-transition metal alloys, and another type based on Zirconium or hafnium alloys (Lubersky, 1983). He describes the first type as containing 80 atom percent iron, cobalt or nickel with the remainder being boron, carbon, silicon, phosphorus or aluminium. Staniek and Hornbogen (1989) have conducted a thorough investigation of alloys and their chemical compositions. They further studied the influence of the alloy composition on the microstructure of the surfaces of eutectic binary $\text{Fe}_{83}\text{B}_{17}$ and $\text{Fe}_{83}\text{C}_{17}$ when being lased. The glass forming ability (gfa) of $\text{Fe}_{83}(\text{B}_x\text{C}_y)_{17}$ ($\text{X}:\text{Y}=25:75; 50:50; 75:25$) caused them to conclude that the Fe-B system is good and Fe-C is to be neglected.

Finally, since hardness, ductility, and strength in formed metallic glasses were the foremost reasons for conducting this experiment, some properties of $\text{Fe}_{80}\text{B}_{20}$ that have been studied by Gilman (1983) follows. According to Gilman (1983), yield stress of $\text{Fe}_{80}\text{B}_{20}$ glass is in excess of 525000 psi (3620 Mpa) or 100 dph which is better than almost all ferrous materials as shown in Table 1. By manipulating the alloying elements in terms of percentage, volume ratio and additive substrates, an even stronger metallic glass could be made. For example, as illustrated in Figure 4, when a metallic glass is made by lasing and a

composition of $\text{Fe}_{75} \text{B}_{25}$, the hardness is 1300 dph which in return translates a yield stress of 575000 psi (3960 Mpa).

Industrial Carbon Dioxide Laser

Laser has been in practical use for nearly three decades. The idea of its invention has been credited to H. G. Wells's famous novel, *The War of the Worlds*. This book was written back in 1896 (Siegman, 1987, p. 1). In that novel, Wells described this phenomena as the tool used by Martians when they invaded the Earth. By referring to the Martians, Wells wrote that: "they are able to generate an intense heat in a chamber of practically absolute nonconductivity." He further elaborated on this idea by calling the intense heat projected in the form of a "parallel beam against any object they choose." This description by Wells fits precisely the way an industrial CO_2 laser operates. Although the novel "The War of The Worlds" was written some 92 years ago, it was not until 1960 that the very first optical-frequency laser device, the pulsed ruby laser was successfully developed and operated by T. H. Maiman of the Hughes Research Laboratories in California (Siegman, 1987, p.2).

Since 1960 the laser has advanced quite rapidly. Many applications of laser have been discovered in a wide range of fields from medicine to communication and from defense to industrial applications. According to Siegman (1987), the

total sales of laser systems around the world has reached the level at about 4-5 billion dollars in 1984 followed by an annual growth of 30% or more in recent years. This figure is for the sales of lasers in practically all the areas discovered so far, e.g. scientific, engineering, industrial, medical, and military. Perhaps the net sales of lasers at the international level would be approximately \$14 billion for the year 1990 based on the previously discussed information. This is the degree of importance of laser and its applications which could indicate the wide spread use of billion for the year 1990 based on the previously discussed information. This is the degree of importance of laser and its applications which could indicate the wide spread use of laser usage at our time.

The most commonly used industrial laser in metal working today is the carbon-dioxide (CO_2) gas laser (Sanderson, 1983). This type of laser is capable of generating an extremely high power output at a wavelength suitable for the processing of different materials. The wavelength required for the surface treatment of metals is 10.6 microns. Because there is no existing material that can be converted into flexible optical fibers that could be transparent enough at this wavelength, a complex multi-mirror system is adapted inside every laser to facilitate this procedure. It has been pointed out by Sanderson (1983) that an industrial CO_2 laser is capable of generating

wavelengths from 9 microns to 11 microns to have the required flexibility for the multi-mirror system.

Carbon dioxide (CO_2) is not the only gas used in an industrial CO_2 laser. Actually there are two other gases required. Carbon dioxide gas is the primary component and acts as the source of photon generation (Sanderson 1983). The second gas used is nitrogen. Nitrogen is utilized to provide assistance for sustaining and reinforcing the lasing action by "transferring energy" to and exciting CO_2 molecules to their highest level. The third component used is the helium gas. This gas provides cooling within the laser cavity by allowing CO_2 molecules to drop from low energy levels to ground states so that a continuous population inversion can be maintained. Helium makes 80% to 90% of the gas moisture used in a CO_2 laser. Nitrogen and carbon dioxide on the other hand form the remaining 10% to 20% of gas mixture on equal bases (Sanderson, 1983).

The amount of energy provided by the focused high-power laser beam supersedes the conventional methods with the exception of annihilation of matter (Letokhov & Ustinov, 1983). A focused high-power laser beam, as described by Letokhov and Ustinov (1983) is capable of generating 10^{10} - 10^{12} joul/ cm^3 energy density which is considerably greater than that generated by chemical explosives (10^4 j/ cm^3) and is comparable to that generated by nuclear explosives (10^{10} - 10^{11} j/ cm^3). Also it is capable of generating power density

at the rate of 10^{20} - 10^{22} watt/cm³, compared to 10^9 watt/cm³, and 10^{16} - 10^{18} watt/cm³ by nuclear explosives.

Considering the extraordinary amount of energy density generated by a laser beam, if this energy was converted into thermal energy via a "condensed medium," the temperature of this medium will reach an extremely high degree of up to "hundreds of millions of degrees" which is precisely the basis for the use of high power lasers for a host of industrial applications in which a controlled thermonuclear fusion takes place (Letokhov & Ustinov, 1983, p. 9). An industrial CO₂ laser operates on the same principle when utilized for the advancement of metallurgical studies.

The process of operation of a CO₂ laser is rather uncomplicated and straight forward. By the process of stimulation, photons are released from CO₂ molecules. These photons possess energy. The principal wavelength of the emitted radiation from CO₂ is 10.6 microns (Sanderson, 1983). Since more than 10% of which electrical energy (used for the excitation process) converts into light energy in a typical CO₂ laser, Sanderson (1983, p. 18), concluded that CO₂ lasing process is "the most efficient" of the available lasing processes. This high efficiency and practicality, makes the industrial CO₂ laser a very capable machine for adaptation in the process of laser surface treatment in metallurgy. Needless to point out that other similar applications in materials processing and metalworking have

an equal chance of taking advantage of the conveniently practical aspects of utilizing an industrial CO₂ laser. There are a wide range of industrial CO₂ lasers in use today. Multi-Kilowatt power outage from such device is very common. For all practical purposes a 1200 watt pulsed laser was used for the purpose of conducting the surface heat treatment of the specimens used in this investigation.

CHAPTER 3

METHODOLOGY

Several steps were taken before the actual lasing of the specimens. This action was done to facilitate the overall procedure and to assist the exactness and accuracy of the planned processes. In a similar fashion, it was necessary to go through certain procedures after the completion of the lasing process to facilitate and to speed up the testing process. Attempts were made to make note of every possible detail that had any bearing on the outcome of this investigation. This study was carried out in six stages as outlined in the following figure.

Preparation of Materials

The materials used for this investigation consisted of a base metal and three additives or otherwise called agents. The base metal was gray cast iron. Economic, availability, versatility, and practicality were identified as reasons for the selection of gray cast iron. Boron, cobalt, and silicon were the three agents use for adding to the base metal while lasing. Each one of these three additives possess certain characteristics in regard to its effect on hardness, corrosion and temperature. Boron greatly contributes to the resistivity of the alloy to heat, cobalt has desirable properties concerning resistivity to corrosion and silicon

Figure 8. Stages of the testing procedure.

acts as a catalyst in forming the glassy state. Studies conducted by Mazumder et al. (1985), Fahmy and Tabrizi (1988), Fahmy and Helzer (1988) and others also contributed to the selection of the three agents discussed above.

The gray cast iron block was obtained from the science laboratory of Northern Illinois University in Dekalb, Illinois. The block was a cylinder with dimensions of 5 inches in diameter and 15 inches in length (5_{in} X 15_{in}). A survey of five local foundries in Dekalb, Rockford, and Marengo, Illinois demonstrated that the type of cast iron obtained was the most common and most widely used for different applications which reinforced the preset intention of selecting gray cast iron as a common metal for various purposes.

Boron was purchased in powder form (150 grams) from Chromtech Corporation. Cobalt was obtained from the Department of Industrial Technology, University of Northern Iowa and silicon was attained from the Chemistry Department at Northern Illinois University. Extra care was taken to assure the purity of the substances at an acceptable range.

Machining of the Specimens and Mixing of the Agents

The obtained cast iron block was cut on the edges and as a result a cubic rectangle with the dimensions of 15 X 3 X 4.5 inches was made. This block was further cut at one-inch intervals and from the 15 pieces, 12 were selected.

Each specimen was surface ground using an automatic surface grinder. The process of grinding was designed to generate the least amount of energy in the form of heat on the surface due to the friction. This action provided assurance that the atomic structure of the cast iron remained intact. Slowest number of revolutions per minute (125 rpm) and intervals of .002 inch were programmed to the grinding machine. A coolant was used in the form of liquid soap mixed with water to remove the excessive heat of the surface while being ground in addition to remove the metal residue.

After the surface finishing process, each of the twelve specimens were placed on a horizontal abrasive cut-off saw for the purpose of machining grooves. Three different grooves were machined on each specimen. The shapes of the grooves were: semi-circle (radius), 45 degree angle cut, and 90 degree angle cut. Exact specifications of each groove are given in Table 2.

As was outlined in the research questions, three ratios of mixtures of agents were used based on weight. The first ratio was 30% cobalt, 30% silicon, and 40% boron. The second ratio was 25% silicon, 25% cobalt, and 50% boron, and the third ratio was 40% silicon, 40% cobalt, and 20% boron. The supervisor of laboratories at the Department of Chemistry, Northern Illinois University conducted the mixing of the agents based on the prescribed ratios. After prepared mixtures were obtained, codes A,B, and C were

Table 2

Groove Shape and Depth Specifications

Specimen Number	Depth in inch	Groove No. 1	Groove No. 2	Groove No. 3
1	.020	45 Degrees	90 Degrees	Semi Circle
2	.020	45 Degrees	90 Degrees	Semi Circle
3	.020	45 Degrees	90 Degrees	Semi Circle
4	.030	45 Degrees	90 Degrees	Semi Circle
5	.030	45 Degrees	90 Degrees	Semi Circle
6	.030	45 Degrees	90 Degrees	Semi Circle
7	.040	45 Degrees	90 Degrees	Semi Circle
8	.040	45 Degrees	90 Degrees	Semi Circle
9	.040	45 Degrees	90 Degrees	Semi Circle
10	.060	45 Degrees	90 Degrees	Semi Circle
11	.060	45 Degrees	90 Degrees	Semi Circle
12	.060	45 Degrees	90 Degrees	Semi Circle

assigned to the first, second, and third mixing ratios. Table 3 illustrates the combined coding of mixture ratios and groove sizes.

Vacuum Emission Spectroscopy

Precise determination of the quantity and quality of all the involved elements was determined based on available technology. The most recent innovation in determining up to and perhaps exceeding seventy metallic and metalloid elements in a material, is the technology of spectroscopy. There are two kinds of spectroscopy: vacuum emission spectroscopy and atomic absorption spectroscopy (Alexander, 1985).

From the 12 prepared samples, 1 was randomly selected and was tested by the metallurgical laboratories of Caterpillar Corporation in Aurora, Illinois. A computerized VES equipment made by Johnson Control Corp. called AUTOCOMP 81 was utilized for this procedure. The specimen A-40 was selected and the outcome of the results of its composition is presented in Table 3 by percentage weight.

At least five different locations were identified for the purpose of this test. Each location was measured three times. Forty five different locations throughout the specimen A-40 were tested for the amount of available elements in the gray cast iron and the results were averaged by the computerized machine. The specimen was then kept for

Table 3

Mixture Ratio and Groove Size Coding

Specimen	% Silicon	% Cobalt	% Boron	Groove depth in mm	Groove depth inch
A 20	30	30	40	.50	.020
A 30	30	30	40	.75	.030
A 40	30	30	40	1.0	.040
A 60	30	30	40	1.5	.060
B 20	25	25	50	.50	.020
B 30	25	25	50	.75	.030
B 40	25	25	50	1.0	.040
B 60	25	25	50	1.5	.060
C 20	40	40	20	.50	.020
C 30	40	40	20	.75	.030
C 40	40	40	20	1.0	.040
C 60	40	40	20	1.5	.060

further references. Table 4 shows the collected data for this procedure.

Table 4

Chemical Composition of Gray Cast Iron Specimen Determined by Vacuum Emission Spectroscopy

Alloys	Percentage Weight %
Fe	93.719
C	3.06
Mg	.85
P	.036
S	.124
Si	1.78
Ni	.05
Cr	.13
Md	.05
Cu	.14
Al	.011
Ti	.04
Va	.01
B	.00

Laser Processing

Laser processing is a rather new technology and due to the cost associated with purchasing and maintenance, its availability is very limited. At the time of conducting this experiment, Iowa Laser Technology, Cedar Falls, Iowa had the needed machinery with the desired specifications for this investigation. An industrial carbon dioxide laser was utilized for the process of lasing the 11 specimens.

An industrial laser consists of three main elements: (a) the laser material, (b) a stimulating device for that material, and (c) the laser material must be retained in a cavity that will allow amplification by repeated reflections of light (Budinski, 1988). The laser material is then excited by pulsing of powerful flash lamps aimed at it. Ruby crystals (alumina/chromia) were used in the early days as laser materials. Basically, when high-intensity light excites the already at rest energy level electrons inside the tube, some of the electrons from atoms will become excited and when returning to their ground state their energy will be emitted in the form of photon which is coherent and in phase. The existing flash lamps inside the CO₂ laser keep repeating this process over and over until there are more electrons in the excited state than the ground state. The excited electrons at this stage contain their highest energy level of the same phase. Phase energy

in the form of photon will then lase through the end of the crystal that has a partially reflective mirror. At this stage since the beam of photons is coherent, it is then manipulated by a set of lenses for focusing on a desired spot and performing a designed task (Budinski, 1988, p.176).

The materials used in lasers can be solids, liquids or gases depending on the equipment and the application. However, they must be transparent to the excitation energy (flash lamps). In most gas lasers, carbon dioxide (CO_2) gas is the material used as the exciting medium which emits energy in form of electromagnetic radiation. Each type of exciting medium used in a laser produces certain wavelength. This parameter is coupled with the fact that the length of laser cavity is a function of the wavelength emitted from the material used. Consequently, in order to maintain coherence, different types of materials are used for different applications and projects. As discussed in Chapter 2, in order to generate light beams strong enough to have desired impact on the surface of metals, a light wave of between $10_{\mu\text{m}}$ and $11_{\mu\text{m}}$ in length in the infrared region was sought. A typical gas laser material such as CO_2 produces wavelength of $10.6_{\mu\text{m}}$, whereas a solid-state laser such as neodymium doped YAG (Yttrium/Aluminium/Garnet) produces light with a wavelength of $1.6_{\mu\text{m}}$ (Budinski, 1988, p. 176) which simply does not suffice for the metal treatment applications. Therefore, because a light wave of

higher number in length was sought, CO₂ was found to be the practical match for the needs of surface treating of metals.

Because of the reasons discussed above concerning the wavelength of the generated light wave, coupled with the specific wattage power sought in the industrial CO₂ laser, the most practical and convenient type of laser for this experiment was found to be an industrial CO₂ laser with approximate power of 1300 watts. Particularly the fact that a CO₂ laser can produce energy as high as "20 KW with beam diameters as small as 0.1 inch (2.54mm) and as large as 2 inches (58mm)" in either pulsed or continuous mode makes it a remarkable equipment for the purpose of lasing metallic surfaces. This is in contrast to YAG lasers that typically can only produce by up to 2 KW energy (Budinski, 1988, p. 176).

The carbon dioxide laser in Iowa Laser Technology, used for this investigation was a 1300 watts powered machine. At the time of lasing, the ambient temperature was 78± degrees F. The laser machine was set and continued functioning with respect to the following data initially programmed and fed to it. Table 5 shows the specifics of the CO₂ laser at the time of operation.

As shown in Figure 9, the specimens were attached to a table on an x-y rotary positioner. The movement of the positioner was controlled by a computer. After careful measurement of the dimensions of the specimens and the

Table 5

Operating Conditions of 1300 Watts CO₂ Laser in Operation

DESCRIPTION	EQUIPMENT READING
AMBIENT TEMP.	78 DEGREES F $\pm$ 0.5
AMPERES	580~590 Milli Amp DC
VOLTAGE	25 Killovolts DC
SHUTTER	OPEN
CONTROLS	ARM
GAS	OPEN
H.V.	ON
RAMPER	ON
CURRENT	900
CONTIN. DWELL	ON
UP RAMP	0101
DWELL	7500
FUNCTION	Continuous Voltage
FREQUENCY	2.57 per Minute
FIELD INTER.	250.000

carved grooves on them, the computer was programmed to move the beam to the exact location of each groove and after lasing the entire groove, it moved to the second one, and then to the third groove, and so on. All 11 specimens were lased in this fashion.

Since a laser beam is a light beam, like any other light beam, it has to be focused to function properly. For this reason the lens-to-work distance was kept at minimal range. In order to minimize oxidation, during the lasing process a jet of inert gas was directed at the surface of the specimens. The surface reflectivity which is one of the most significant aspects of any lasing process of materials, was dealt with in the following form. Although perhaps more than 90% of the incident laser light usually will be reflected from the surface of a shiny metal, the remaining 10% could cause a problem due to the overheating and the lack of proper speedy cooling rate. In order to deal with this problem, the surface of the specimens were covered by spraying radiation absorbing and self burning chemical components so that they absorbed rather than reflected the laser beam and therefore the surface was heated by radiation.

Although there are a host of different techniques to prepare a matte black surface of the specimens for the absorption of radiant energy, the following four techniques

are practiced in industry more than other techniques (Budinski, 1988):

1. Black chemical conversion coating
2. Black electrodeposits
3. Carbon/graphite spray coating
4. Heat tinting

Iron/manganese phosphate chemical conversion coating is one of the most common methods of radiation conversion in the surface treatment of metals by laser. This chemical component was used for the coating of the surfaces of the specimens in this study. Figure 9 illustrates the actual process that was conducted in Iowa Laser Technology.

The mixed powder with different alloying elements was packed into the grooves and pounded by a small hammer. Packed again and pounded again repeatedly until the groove was completely packed.

The only difficulty associated with this technique was to insure that the agents packed in the grooves were held in close contact with the base of the specimen to avoid vaporization without fusing into the workpiece. By first packing the powder agents as firmly as possible inside the grooves and then covering it with the same chemical components used for coating the entire surface that left no residue after lasing, the powdered alloying elements stayed in close contact with the surface of each groove. By

Figure 9. Schematics of CO₂ laser operation.

Figure. 10 Adapted technique for lasing.

conducting this technique as results indicated later, a desired contact was made between the agents and the surface and assured the proper fusing of the powder agents.

After the completion of lasing of all specimens, they were left at the ambient temperature of 78 degrees F to cool down for a period of one and one half hours. The specimens were then removed to the metallurgical laboratories of the Caterpillar Corporation in Aurora, Illinois for preparation of the testing process.

Sample Preparation

There were three different grooves on each specimen. The first groove was 45 degree angle cut, the second was 90 degree angle cut, and the third groove was a semi-circle cut. Since there were three different mixtures of alloying elements, three specimens containing identical depths were made for each mixing ratio. This was repeated for each of the four depth sizes ranging from 0.020 to 0.060 inch. Therefore, a total of four different depths were machined on all grooves. Table 1 provides information in regard to the specifics of each groove and each specimen.

In order to prepare a sample for different testing such as microstructural analysis, mechanical properties, examinations, and scanning electron microscopy, pieces of each specimen were placed on a standardized cylinder shape bodies made from bakelite. First, specimens were cut in

such a way that no heat was produced in the process. The pieces of carved grooves were approximately 8 X 12 millimeters. Each piece contained the lased area and the base metal which was gray cast iron.

An ISOMET low speed sectioning disc was utilized for cutting the lased samples to overcome the problems associated with the excess of local heat while cutting. The basic concept of the low speed cutting saw as it is illustrated in Figure 11 is that a sample (A) was held in a suitable chuck and was introduced through gravity by a load (B) to a rotating wafering (C) which was coated with a film of lubricant picked up during its rotation through (D) the coolant tank (Buehler, 1983). Extra attention was paid to each operating parameter to secure the best possible result.

The equipment used for making sample holders for metallic specimens operates on both pressure and heat. After placing the cut samples inside the mold cylinder, the cylinder is then filled with a polymeric material such as Lucite or Bakelite. The cylinder cap is then closed and heat is turned on while pressure inside the cylinder is raised by the pump handle, located on the side of the sample maker. Bakelite powders, when simultaneously subjected to a temperature of 150 degrees centigrade and about 5000 psi, harden approximately within 5 minutes.

After placing three pieces in the bottom of the cylinder, bakelite was used and by pressing at the rate of

Figure 11. The principle of low speed saw sectioning.

Note. From Metal digest (p. 4) by Buehler Corp, 1983.

4300 psi for 5 minutes at 150 degrees C temperature, samples were made and each groove piece was marked by number 1, 2, or 3 on the opposite side of the sample. For a total of 11 samples, containing 3 grooves machined on each, 33 pieces were made to be tested. Furthermore, each sample was labeled with reference to the mixture ratio of the substrates and the depth of the grooves, on that particular specimen. As an example, C30 stands for 40% cobalt, 40% silicon and 20% boron while the depth of the grooves was .030 inch or .75 mm.

The produced samples were then ground by utilizing a horizontal watercooled grinder for both rough grinding and fine grinding. The abrasives used were silicon carbide grits of 120, 240, 320, 400, and 600. The direction of grinding was performed with 90 degrees between the positions of one grinding step and the next to avoid scratching of the surface by the removed residue and to assure a proper grinding procedure as illustrated in Figure 12.

Polishing took place in two stages. First, rough polishing was conducted in which fine grinding scratches were completely removed while a flat surface was maintained. A rotating wheel polisher/grinder with a low nap cloth attached to its surface was used. A liquid extender was then applied to provide lubrication. The wheel's speed was set at 200 rpm while variable loading was exerted on the samples to obtain maximum performance from the abrasive

Figure 12. Schematic of grinding and polishing operation.

Note. From "Fine Grinding" by G. Petzow 1990, Metal digest, (Buehler Corp. p. 3).

by the automatic equipment. The second stage was final polishing. This stage was also conducted on a rotating wheel covered with a cloth having slight to moderate nap. Alumina abrasives in the 0.3 to 0.5 micron range was used. The wheel was charged by moistening the cloth with deionized water. Then the alumina was applied to the cloth in a circular bead. The wheel's speed was set at 250 rpm and the cloth was moderately moistened but not entirely wet. In order to minimize directional polishing effects, the samples were rotated in a direction opposite to that of the wheel rotation. The prepared samples were then placed next to some silica gels and removed for microstructural analysis. Silica gels are known to absorb humidity rapidly and efficiently. Taking this action provided assistance in maintaining a rust-free surface of the samples until they were microstructurally analyzed.

Microstructural Examinations

A careful microstructural examination was conducted to investigate the individual phases or microconstituents, phase transformation, grain size, cracks, porosity, and segregation of alloying elements in each specimen. The first action in this regard was taken for the examination of metallic glass formation. In doing so, some randomly selected pieces of the formed layers were selected and then prepared for the X-ray diffraction test. Facilities of the

analytical laboratory of the department of Geology at Northern Illinois University were utilized for this purpose. After cutting the pieces from the lased areas of the samples, each piece was then mounted on a sample holder suitable to fit the X-ray diffraction machine. A total of five samples were tested for the detection of diffused patterns that are characteristics of glass and non-crystallinity. Furthermore, in order to study the effects resulted by the lasing and addition of alloying elements on the surface of the base metal, special attention was paid to the comparison between the characteristics of pearlite areas versus martensite areas.

Pearlite matrix was closely examined for ingredients such as: sulfide inclusions, Titanium Nitrides, Graphite flakes, Steadites, and Ferrites. Although etching makes the microstructure visible to the microscope by highlighting the composition differences, differences in orientation of grain structure, and selectively attached grain boundaries (Pollack, 1988, p. 71), however, in order to inspect all possible outcomes, some samples were examined unetched and several magnification ranges were utilized.

Starting from 50X magnifications, 100X, 200X, 500X, 1000X, and finally 5000X magnifications were utilized for Figures 13 to 19. A camera with ability of magnification up to 5000X and picture taking was utilized. Micrographs used in this text were taken by the aforementioned camera.

Figure 13. 500X magnification illustration of the existence of microcomponents such as sulfide inclusion, graphite flake, titanium nitride as well as ferrite in the laser treated B-20 #1, samples (25% cobalt, 25% silicon, 50% Boron, and .5mm depth).

Figure 14. 500X magnification illustration of microcomponents such as graphite flakes, steadite, titanium nitride and sulfide inclusion in an A-30 #1, sample. (30% cobalt, 30% silicon, 40% Boron, and .75mm depth).

Figure 15. 50X and 1000X magnification illustration of the texture and the difference between heat affected zone (HAZ) areas and other areas not affected by the radiation in A-60 #3 sample (30% cobalt, 30% silicon, 40% Boron). The microstructure shown in the photo above shows the martensitic structure that was created as a result of the laser melting that part, and the subsequent rapid quenching accompanying that process. It also shows the interface between the molten [and resolidified] area and the H.A.Z.

Figure 16. 50X and 500X magnifications illustration of the lased, fusion line and heat affected areas of the B-60 #3 sample. (25% cobalt, 25% silicon, and 50% Boron) The martensitic [needle shaped] structure that formed as a result of the rapid cooling after lasing is also evident in the pearlitic structure in the background.

Figure 17. 50X and 500X magnification illustration of lased, fusion line and heat affected areas of C-60 #3 sample (40% cobalt, 40% silicon, 20% boron). The microstructure shown in the above photo shows the three areas of the surface affected by the laser. Lased area is the foreground connected to the fusion line. In the background heat affected zone is shown.

Pearlite 1000 X Martensite

Figure 18. 1000X magnification illustration of Martensite and Pearlite in a B-60 #3 sample (25% cobalt, 25% silicon, and 50% boron). The above microscopic photo shows the two textures of pearlite and martensite side by side. The two areas are separated by the degree of refinement as well as the graphite flakes which is one of the characteristics of gray cast iron.

1000 X Martensite

Figure 19. 1000X magnification illustration of Martensite. The martensitic structure is shown as well as the graphite flakes as a characteristic of gray cast iron. Some of which were broken into smaller pieces as a result of the lasing process. Also shown in the background are some carbide precipitates due to the lasing process and the rapid quenching that accompanied it.

Mechanical Testing

Mechanical or otherwise known as hardness testing; is the measurement of the degree of resistance to external force by a material. Depending on the nature of its application a host of different definitions of hardness testing exist. Elaboration and explanation on the hardness testing from the point of view of testing of materials was given by Davis et al (1982, p. 30), as "a measure of the resistance to surface indentation or abrasion." Despite the stated definition by Davis, he later pointed out in his book that the fundamental "physics" of hardness is not yet clearly understood and from a number of different arbitrary definitions of "hardness," the term "resistance to permanent indentation under static or dynamic loads" is more acceptable and perhaps more frequently used.

Although there are a host of different methods of hardness testing of materials such as compression, tensile, torsion, fatigue and creep, as well as many methods in non-destructive testing in practice today, perhaps the most common technique for metals in general and iron and steel in particular are: Rockwell, Tukon, Vickers, and Brinell (Davis et al., 1989). The hardness testing used in this investigation was conducted by a Rockwell Hardness Machine on its C scale at the metallurgical laboratories of Caterpillar Corporation in Aurora, Illinois.

As mentioned earlier, each sample had three grooves machined on its surface and every groove represented a different depth and shape. Each sample was tested an average of 27 times using the Rockwell hardness testing machine. This is due to the fact that there were three different zones on each laser treated groove: (a) the lased area, (b) fusion line which is the threshold of the base metal with the lased alloying elements, and (c) heat affected zone (HAZ) which is the area affected by the energy of the radiated heat. Typically, for hardness testing measurement of every zone, three different points are measured and then the average of the three measurements is recorded. Consequently, a total of 9 measurements were taken for every piece and 27 such measurements for each sample were recorded.

The Rockwell hardness number (HRC) data obtained of all the samples used in this study are listed in Tables 6, 7, and 8. It is noteworthy to mention that the average HRC for the base metal (gray cast iron) was 32. The collected data reflect several points. Each point is explained on the related table. Some specifications such as rise in the degree of hardness of lased areas are shared throughout all tables. Furthermore, it seems that neither the depth nor the geometry of the grooves had any measurable effect on the hardness values in all areas.

Table 6

Hardness of 30% Cobalt, 30% Silicon, and 40% Boron Samples
in HRC

SAMPLE CODE	DEPTH OF GROOVE	SHAPE OF GROOVE	HARDNESS OF DIFFERENT AREAS		
			LASED AREAS	FUSION LINE	AVE (HAZ) 2 SIDES
A-20	.50mm OR .020 in.	45 DEGREES	70	47	63
		90 DEGREES	70	49	63
		SEMI- CIRCLE	70	57	60
A-30	.75mm OR .030 IN.	45 DEGREES	69	56	63
		90 DEGREES	68	56	62
		SEMI- CIRCLE	70	50	61
A-60	1.5mm OR .060 IN.	45 DEGREES	70	47	58
		90 DEGREES	70	60	61
		SEMI- CIRCLE	70	60	63

Note. The following point was one of the observations deduced from this table: The hardness value of the laser treated areas are the highest, as expected.

Table 7

Hardness of 25% Cobalt, 25% silicon, and 50% boron samples in HRC

SAMPLE CODE	DEPTH OF GROOVE	SHAPE OF GROOVE	HARDNESS OF DIFFERENT AREAS		
			LASED AREAS	FUSION LINE	AVE (HAZ) 2 SIDES
B-20	0.50mm OR .020 in.	45 DEGREES	70	56	63
		90 DEGREES	63	45	58
		SEMI-CIRCLE	70	58	63
B-30	0.75mm OR .030 IN.	45 DEGREES	NO TEST	NO TEST	60
		90 DEGREES	70	50	62
		SEMI-CIRCLE	70	56	61
B-40	1.00mm OR .040 IN.	45 DEGREES	70	47	58
		90 DEGREES	69	60	61
		SEMI-CIRCLE	NO TEST	60	63
B-60	1.5mm OR .060 IN.	45 DEGREES	70	57	62
		90 DEGREES	70	48	63
		SEMI-CIRCLE	70	48	61

Note. The following point was one of the observations deduced from this table: Neither the depth nor geometry of the grooves seem to have any measurable effect on the hardness value in all areas.

Table 8

Hardness of 40% cobalt, 40% silicon, and 20% boron samples in HRC

SAMPLE CODE	DEPTH OF GROOVE	SHAPE OF GROOVE	HARDNESS OF DIFFERENT AREAS		
			LASED AREAS	FUSION LINE	AVE (HAZ) 2 SIDES
C-20	0.50mm OR .020 in.	45 DEGREES	69	57	61
		90 DEGREES	65	50	62
		SEMI-CIRCLE	64	60	62
C-30	0.75mm OR .030 IN.	45 DEGREES	65	60	61
		90 DEGREES	67	61	62
		SEMI-CIRCLE	64	50	61
C-40	1.00mm OR .040 IN.	45 DEGREES	NO TEST	NO TEST	61
		90 DEGREES	66	53	64
		SEMI-CIRCLE	67	53	62
C-60	1.5mm OR .060 IN.	45 DEGREES	70	57	62
		90 DEGREES	64	55	63
		SEMI-CIRCLE	70	50	62

Note. The following point was one of the observations deduced from this table: As expected the HAZ still retained some modifications of its hardness values over the base [average 61-62 vs 32].

CHAPTER 4

ANALYSIS OF THE RESULTS

Introduction

The main purpose of this study was to investigate the possibility of forming an amorphous metallic layer on the surface of gray cast iron by adding boron, cobalt, and silicon as agents and utilization of the radiation emitted by an industrial carbon dioxide laser. In so doing a typical industrial laser with capacity in the range of 1000~2000 Watts power was used for the lasing process and infusion of the alloying elements onto the base metal surface. Results obtained from the analytical laboratory of the department of Geology at Northern Illinois University indicated that the formed layers on the surface of gray cast iron contained certain degree of non-crystallinity on the formed layers (Appendix B), hence the main point of this investigation was confirmed. Second to the main purpose, were a number of questions asked about the quality, quantity, and the characteristics of the formed layer based on the possibility of such a process. The following eight questions are the main theme of this study. They are interrelated. Confirmatory response on any one question could very well depend on the positive outcome of another. There is a sequence to these questions and each possesses a certain degree of importance in connection with the overall

picture of the study. It is comprehensible that some would take longer discussions than the others. This is not indicative of importance of that particular question, but merely reflects the degree of need for elaboration and explanation on the part of the question.

The Research Questions

Question One

How feasible was the forming of an amorphous metallic layer (silicon, cobalt, and boron) on the surface of gray cast iron by utilizing an industrial carbon dioxide laser? To answer this question, a series of tests were conducted. X-ray diffraction, mechanical, microstructural, as well as stress tests were the order by which testing took place. The gathered data which was the measurement of the reflected waves from the surface of lased areas indicated no pick at any angle. Intervals of five degrees from zero to 90 degrees were used in conducting the measurement. The obtained graph from x-ray diffractometer illustrated a curve shape line that resulted from the connection of measured reflected points. This is an indication of metallic glass formation. Therefore, analysis of the results obtained from the x-ray diffraction test indicated that certain degree of diffused patterns were observed on the lased areas of the treated surfaces (Appendix B). This result was the confirmation of the formation of metallic glass and

therefore, a non-crystalline structure. Based on the results obtained from different testings this answer means that it is conceivable to add three agents: boron, silicon, and cobalt on the surface of a gray cast iron and after exposure of such surface to the radiation emitted by a 1300 watts industrial carbon dioxide laser, a new layer will be produced that will adhere to the cast iron. Furthermore, the hardness of such a layer is by far greater than that of the original base metal, the gray cast iron. The results obtained from mechanical hardness testings in particular indicated that the main task of this investigation was accomplished. The base metal had a hardness of 32 HRC. The type A samples had an average of 69.7 HRC at the lased areas. The type B samples had an average of 69.2 HRC, and the type C samples had an average of 66.45 HRC. Comparison of the degrees of hardness between the base metal (gray cast iron) and the formed layers on its surface indicated that the resistivity of the base metal to indentations of foreign objects increased drastically. This is improvement in the hardness of the base metal. Therefore, since there is a high degree of improvement in the hardness number of the lased surface, it is evident that this procedure produced a certain degree of quantitative improvement.

Question Two

The second research question was: what effects would result from adding silicon, cobalt, and boron in the

percentages of 30%, 30%, and 40% (sample A) on the mechanical and bonding properties?. Since one of the concerns of this study was to evaluate the hardness properties and microstructural properties, the gathered results in reference to the aforementioned properties, follow: Table 6 and Figure 20 are both representing the results obtained from the hardness testing of all samples with the mixing ratio of A (30% Co, 30 % Si, and 49% B), numerically as well as graphically.

As it is evident from the results, higher values of hardness testing were achieved in the formed layers. Next to the lased areas of the formed layers was the area called "fusion line" which was the threshold of the lased areas and HAZ. Referring to the explanations in chapter 2, there was also an area called heat affected zone (HAZ) which is the area around the lased area and is affected by the heat of fusion, in addition to two areas previously discussed. Mechanical and microstructural properties of all the three area aforementioned have been studied. Figure 21 demonstrates the microstructural view of the formed layer on an A-60 #3 sample.

Based on the mechanical testing of all samples, it is noteworthy to mention that the fusion line has a lower degree of hardness compared to that of both lased as well as heat affected zone areas. Perhaps this point could be attributed to the degree of adherence on the fusion line.

Figure 20. Graphical presentation of the hardness measurements for samples Type A.

A60 #3 Fusion Line Separates the Lased Area and HAZ

Figure 21. 1000X Magnification of the Microstructural View of the formed layers and the base metal in an A-60 #3 sample (30% silicon, 30% cobalt, 40% boron). In the microstructure shown in the above photo, the heat affected zone (HAZ) is shown in the foreground which is separated by a line from the background or the lased area called fusion line.

B60 #3 Separation of Lased Area and Haz by Fusion Line

Figure 22. 1000X Magnification of the microstructural view of the formed layer and the base metal in a B-60 #3 sample (25% cobalt, 25% silicon, 50% boron). The curved line between the dark and the light areas of the microstructural photo above is the fusion line. It also shows inclusions and elements such as graphite flakes.

C60 #3 Separation of Lased Area and HAZ by Fusion Line

Figure 23. 1000X Magnification of the microstructural view of the formed layer and the base metal in a C-60 #3 sample. (40% cobalt, 40% silicon, 20% boron). The above photo shows microstructure of the C-60 #3 sample. Because of the position of photo, the above pearlite structure is more balanced than the previous two with regard to the demonstration of the separation between the lased area and HAZ.

Explanation of this phenomena suggested by experimental results is as follows. The radiated energy absorbed by the threshold line of the lased areas and their immediate surroundings where the radiated energy is not sufficient to complete the full cycle of heating, melting, and rapid cooling in comparison to the surfaces with alloying elements. Consequently, some alloying elements that were still present on that line had not completed their melting caused by lasing. Since surface of this line was neither a completely lased area nor it was the base metal that could be heat treated in the same fashion as the heat affected area zones, fusion line possesses a lower degree of hardness in comparison with the other two areas. Another point observed in the comparison of the results of the hardness testing is that the hardness of the fusion lines increased as the depth of grooves became deeper. Further discussion of the details of this point will be followed later. In all, measured hardness numbers indicated that by mixing cobalt, silicon and boron at the rate of 30%, 30%, and 40% and adding to the surface of gray cast iron, by lasing the surface, a harder metal will be formed. In addition, microstructural analysis of the formed layer was indicative of a more homogeneous texture that was more resistant to corrosion.

Question Three

What effects would result from adding silicon, cobalt, and boron in the percentage of 25%, 25%, and 50% (sample B) on mechanical and bonding properties?. In order to answer this question, results of mechanical (hardness) and microscopic testing of the formed layer need to be studied.

Similar to the previous question, a total of 4 samples each containing 3 grooves were utilized for this stage. All samples contained one groove of a semi-circle shape, one groove of 45 degrees cut and one groove of 90 degrees cut. Four different depths of .5mm, .75mm, 1mm, and 1.5mm were carved on the four samples used. The pre-mixed agents in the order described above were applied in the grooves and then lased. Table 7 as well as Figure 24 provides the specific results obtained for each groove in regard to hardness testing. Four areas were also labeled as: "no-test." Cavity formation and/or porosity are the reasons for which specimens were not tested.

Data from the mechanical hardness testing of the B samples were used to draw the conclusion to question three. According to Table 7 a high degree of hardness (70 HRC) is achieved if boron is mixed with cobalt and silicon in the ratio of 50%, 25%, and 25%. Although, the obtained result indicates the fact that boron contributes enormously to the improvement of hardness, in comparison with the previous mixing ratio, a substantial improvement has not been

Figure 24. Graphical presentation of the hardness results obtained for B samples.

detected. In fact, hardness is the same in both cases. One conclusion is that, once the effective level of mixing ratio with regard to boron is reached, additional utilization of it will not contribute to more improvements on the part of the hardness values.

Question Four

What effects would result from adding silicon, cobalt, and boron in the percentages of 40%, 40%, and 20% (specimen type C) on mechanical and bonding properties? This question differs from the previous two, mainly due to its reduced percentage of boron content. Boron is considered as an agent that contributes enormously to the hardness of metallic surfaces compared to other agents (Budinski, 1988). Figure 26 demonstrates the properties of boron as a hardening agent for the surface treatment of metals in comparison with other substrates. As it is evident from that figure, the highest value of hardness is achievable by the treating of the metallic surfaces with boron carbide. Considering this point, the outcome of this stage of the investigation is in agreement with the expected results and is reinforcing the previously discussed properties of boron.

According to Table 8 and Figure 25, hardness degree of lased areas is on the average four to five HRC lower than those of the previous treatments with higher percentages of boron. The boron content is only 20% in this stage versus 40% and 50% in the previous two treatments. A very vivid

Figure 25. Graphical presentation of the measured hardness for samples type C.

and noticeable relation in the increase of hardness is observed as boron content is raised and the opposite (a decline in the degree of hardness) is observed when boron content was reduced.

Table 8 is the results of the hardness testing of this stage and Figure 25 is the graphical presentation of those results. Compared to the two previous stages, the degree of hardness in all three areas of each groove is considerably lower which can be directly attributed to the low percentage of boron content in the mixed agents. The only "no test" results belongs to 1mm deep, 45 degree groove that could quite possibly be attributed to the existing cavity or porosity in the sample.

Boron, has proven to be a contributing factor to the attainment of higher hardness numbers when utilized properly. Presumably, there is a range of mixing ratios for boron to be most effective in producing a desired hardness in metals when alloyed with other elements. One interpretation of the behavior of the ratio of boron mixture pertinent to this question, could be that 30% ratio of boron is the lower range of effectiveness for surface treatment.

Question Five

How deep would the formed layer become throughout the laser treated area? This question dealt with the depth of the lased surface areas. Energy power of the laser was the main responsible factor. The basic purpose of this part was

Figure 26. Effects of boron, on the hardness of coating compared with other agents.

Note. From Surface Engineering for Wear Resistance (p. 328) by K. G. Budinski, 1988, Englewood Cliffs, NJ: Prentice Hall.

to measure and compare the depth of the layer in the lased grooves. The results of measurements pertinent to this question were scattered and varied with each groove. The actual formed layers' thickness ranged from 0.045mm to 2.15mm.

Every specimen was cross-cut by the previously described abrasive grinder. Three points were selected on the beginning, middle, and the end of each piece. The depth of formed layers were measured and then averaged. Each specimen therefore, had a depth ranging from 0.045 mm to 2.15 mm that was resulted from averaging of the three measurements. Measured depths varied from groove to groove with respect to the geometrical shape. However, a comparison among the different measured depths suggested that there was no significant relationship between groove geometry and depth of the tested areas. This was translated into an overall conclusion that although some minor variations in the measured depths of different grooves could be observed, however it was not sufficient enough to claim existence of relationship between the geometrical shape of the groove and the depth of the treated area.

Question Six

What effects would the formed layer have on the base metal and how well will it adhere?. The following figures demonstrate clearly the bonding between the formed layer and the base metal. Lack of gap between the surfaces, coupled

with homogeneity of the texture throughout the bonded areas is indication of a quality adherence. This observation was tested mechanically as it will be explained in the following pages. Different magnifications are used for microscopic photos. Among the observed microstructures on the threshold matrix between martensite and pearlite, granite flakes, steadite, titanium nitride, sulfide inclusions, and ferrites are prevailing. There were no negative effects observed on the base metal that could in any way be attributed to the alloying elements. Gray cast iron (base metal) possessed same composition and hardness before and after the process of lasing. There was however, an increase in the hardness number of the base metal immediately surrounding the lased area (HAZ) which is directly associated with the heat treating of metals and would be observed under other circumstances as well. A compression testing was conducted to test the degree of adherence of the alloying elements to the base metal. A Tension-compression testing machine with capacity of 65000 psi was used for this step. A pressure of 55000 psi was exerted on the surfaces of some of the lased areas that were selected randomly. No crush, fracture, separation of lased pieces or any other default was observed. Furthermore, microscopic photos illustrated a solid adherence throughout the lased areas with the base metal. Figures 27-28 are the visual demonstrations of the points discussed.

Question Seven

How homogeneous would the newly formed surface become? This question requires a certain degree of elaboration. The notion of homogeneity is rather proportional and not an exact entity like some other properties. For all practical purposes, the main intention of this question was to investigate the "epidemic" and unity of formation of the alloying elements across the board. Hence, to demonstrate that the formed layers are of the same components and microphase, for all the similar mixing ratios, the question would be answered.

It is inevitable that certain microstructures such as cracks, graphite flakes, grain boundaries, sulfide inclusions, etc. appear in the texture of a heat treated metal. This study was no exception. The main theme of this question however, was to provide exhibitions leading to illustration of existence of such microstructures in the treated samples. The following Figures (29-31) provide such exhibitions. Different mixing ratios and depths were utilized for this purpose. Another evidence of the formation of a solid and homogeneous surface by lasing was the homogeneity in responding to the hardness testing. As shown in Tables 6 through 8, the hardness values were constant throughout each mixed ratio which was another indication of homogeneity of the formed layers.

Figure 27. 500X Magnification of the microstructural view of the formed layers bonded to the base metal (A60 #1 sample). The above microscopic photo shows the solid connection between the base metal and the laser area. Homogeneity is also observed on the connection line.

500 X

B40 #2

Figure 28. 500X Magnification of the microstructural view of the formed layer and the base metal view of the formed layer bonded to the base metal (B40 #2 sample). Lack of undesired elements such as cracks, cavity, etc. was indicative of a solid adherence between the base metal and the lased areas as it is shown in the microscopic photo above.

500 X

A30 #1

Figure 29. 500X Magnification of the demonstration of homogeneity in the texture of an A-30 #1 sample.

500 X B30 #1 Near Fusion Line

Figure 30. 500X Magnification of the demonstration of homogeneity in the texture of a B-30 #1 sample.

1000 X

C30 #1

Figure 31. 500X Magnification of the demonstration of homogeneity in the texture of a C-30 #1 sample.

Question Eight

Based on the existing standards and testing methods, what would be the microstructural analyses and the microhardness of the formed layer?. The metallurgical laboratories of The Caterpillar Corporation in Aurora, Illinois provided assistance by making available the use of their facilities for this stage of the investigation.

Johnson Control, Autocomp 750 Vacuum Emission Spectroscopy, Nikon metallograph, automatic bakelite machine, and Rockwell hardness testing machine are some of the equipment used in the course of conducting tests for microstructural as well as hardness of the prepared samples. Although some properties of the microstructures of the samples were explained earlier, the following detailed figures provide more depth into the matter in question.

The formed layers of each photograph contains within it, microphases such as graphite flakes, sulfide inclusions, steadite, titanium nitrides, whereas the surface of the base metal consists of typical textures which are typically observed in gray cast iron. Figures 32-34 provide visual demonstration of some of the existing microphases in the texture of the lased areas. A comparison between the microstructure of the base metal and the lased surface indicated that the surfaces possessed certain elements that were not observed in the base metal. Elements such as martensite phases that developed due to laser heating and

rapid quenching. This comparison was the base for the observations in the detection of new microphases formed in the lased areas.

Since gray cast iron has been around for a very long time and therefore its properties have been studied extensively, almost every microphase present in its texture is readily known and could almost exactly be anticipated. However, due to the heat treatment as well as the addition of substrates such as cobalt, silicon, and boron, the lased surfaces of gray cast iron consisted of microphases that were not observed in the base metal. Microphases such as martensite, carbide, graphite flakes, sulfide inclusions, titanium nitride, and steadite were observed. Some ferrites and graphite flakes were also observed on the threshold of the lased and the base metal areas.

Figure 32 is an unetched microscopic photo of the A-30 samples. This specimen contained 40% boron. Figure 33 is also an unetched microscopic photo of the B-30 samples. This specimen contained 50% boron. Figure 34 is an unetched microscopic photo of the B-60 samples as well. Although this specimen contained 50% boron, however, the depth of the groove was different. Presence of the microphases and their relationships to the percentage of boron content are also noticeable.

Three variables that existed throughout this investigation were the followings. The first variable was

Figure 32. Unetched microscopic view of A-30 samples (30% cobalt, 30% silicon, 40% boron).

Figure 33. Unetched microscopic view of B-30 samples (25% cobalt, 25% silicon, 50% boron).

50 X Unetched B60 #1

50 X Unetched B60 #2

50 X Unetched B60 #3

Figure 34. Unetched microscopic view of B-60 samples
(25% cobalt, 25% silicon, 50% boron).

the ratio of the agents used. The second was the geometrical shape of the carved groove on the surface of the base metal and the third variable was the depth of each groove. Overall analysis suggested that a better and more improved hardness was attained when a higher percentage of boron was used.

Although shape and depth of grooves did not contribute significantly to the overall outcome of this study, however, it appeared that in comparison with the results obtained, they play a minor role. While Tables 6-8 provide exact numbers of HRC with respect to the hardness of different grooves, Figures 35-37 are linear demonstrations of the measured hardnesses in different types of sample.

Figure 35. Linear demonstration of the hardness of type A samples.

Figure 36. Linear demonstration of the hardness of type B samples.

Figure 37. Linear presentation of the hardness of type C samples.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

As was previously stated, one of the major goals of this investigation was to discover the feasibility and practicality of forming metallic glass layers on the surface of gray cast iron using other substrates and a laser beam. This study was conducted according to the proposed procedures. First and foremost sign of an acceptable result in connection to this study, was to achieve a degree of hardness on the formed layer comparable to that of metallic glasses. As it is exhibited in Tables 6 through 8, the achieved hardness on the lased areas of all different specimens are confirming this comparative conclusion. Although the hardness values varied with mixing ratios and to a minor extent with depths and shapes of the grooves, nevertheless, even the lowest value of HRC measured was quite high and was desirable for many applications in different areas. Furthermore, based on the gathered data, it became conspicuously conclusive that boron, when applied, is a major factor in increasing the hardness level of metallic surfaces. Another conclusion was drawn pertinent to this observation on the fact that, adding boron as a hardening agent to the mixture of the alloying elements could only be effective up to a certain level and would not

present much impact once passed that level. This conclusion was drawn by comparing the hardness values obtained by the addition of three different boron content. It was also observed that only a certain degree of depth as well as hardness on the surface of metallic alloys could be attained by the lasing process. Consequently, based on the procedure and the equipment utilized for this study, it became evident that there is a limit to how deep the surface of the base metal could be affected by surface lasing.

The more precise conclusions regarding different stages of the study were as follows:

1. Metals could be treated on the surface for increased hardenability by methods different than traditional and conventional methods.
2. Boron, cobalt, and silicon could be used as alloying elements for the formation of a hardened layer on the surface of metals.
3. There is a certain percentage of mixture for each alloying element by which when used, a desired result could be produced.
4. Silicon, cobalt, and boron could be mixed in the percentages of 30%, 30%, and 40% and can produce a mixture by which an increased hardness on the metallic surface would become attainable.

5. Silicon, cobalt, and boron, could be mixed in the percentages of 25%, 25%, and 50% and still produce same hardness results as the previous mixture ratio.

6. Silicon, cobalt, and boron could be mixed in the percentages of 40%, 40%, and 20% and produce a mixture that will generate less hardened surface than the previous mixtures when applied with laser.

7. Boron as expected, contributed enormously to enhance the degree of hardness of the formed layer, therefore, it is considered a key contributor to the improved characterization of the formed layer in terms of hardness.

Recommendations

Based on the outcome of this study, several recommendations are made:

1. Rapid solidification has a direct relationship with the formation of metallic glasses. More investigations of this concept could enhance the field of metallurgy extensively.

2. Ambient air has been used as the surrounding in which lasing of the metallic surfaces takes place. Studies of different surroundings such as oxygen, nitrogen, etc. could provide more elaboration on the possibility of improvement on the rate of cooling.

3. There are a host of different metals that have the potential of being utilized for the process of surface

treatment by lasing. Other categories of iron such as white, ductile, etc. as well as other metals could be investigated.

4. Deeper carved grooves, e.g. 2mm and more could be made on the base metal for future studies.

5. Boron once utilized properly, is a great contributor to achieving of higher hardness in certain metals. It could be studied more in depth for the amount, and/or ratio in comparison with other alloying elements and method of utilization.

6. Different mixing ratios of the alloying elements used in this study could be investigated. Ratios such as 35% boron, 35% cobalt, 30% silicon, or 45% boron, 30% cobalt, 25% silicon, etc. could be tried.

7. A stronger industrial CO₂ laser in the range of 2500 watts or more could be utilized and results should be monitored for more effective and homogeneous local heat generation.

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Appendix A
Mechanical Testing Analyses
of the Samples

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A0018104 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018104 10/24/90 A20 TEST BLOCK B03A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
0000000000 N.I.U. 0000000000
BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. M 5
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLES
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/07/90 TECH INITIALS LIT
TEST SUMMARY

PREPARATION COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/08/90 TECH INITIALS LIT
01 COMM #1
02 COMM WELD >RC70 #2
03 COMM FUSION LINE >RC70 #3
04 COMM H.A.Z. RC47 RC49 RC57
05 COMM BASE PLATE = RB86 RC63 RC60
TEST NAME 09 MICRO DATE COMPLETED 11/07/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN (
A0018104 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: <1%
06 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
07 COMM NOTE: TRACES OF TITANIUM NITRIDES AND SULFIDES INCLUSIONS
08 COMM HEAT AFFECTED ZONE: PLATE MARTENSITE WITH 30-35% RETAINED AUSTENITE
09 COMM AND MASSIVE CHILL CARBIDES ALONG THE FUSION LINE.
10 COMM (CARBIDES PROBABLY CAUSED FROM INCIPIENT MELTING)
11 MICRO FILE:1535
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN (

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A0018105 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018105 10/24/90 430 TEST BLOCK R086
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
000000000000 N.I.U. 00000000000
BLD AREA LOT-SZ 1ST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. 00000000000
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90 M 3
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/12/90 TECH INITIALS LIT
TEST SUMMARY

SAMPLE PREPARATION COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/12/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD >RC67 >RC68 >RC70
03 COMM FUSION LINE RC56 RC56 RC50
04 COMM H.A.Z. RC63 RC62 RC61
05 COMM BASE PLATE = R086
TEST NAME 09 MICRO DATE COMPLETED 11/12/90 TECH INITIALS LIT
01 COMM BASE PLATE = GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018105 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARRIDES: NIL
05 COMM STEADITE: 41Z
06 COMM STRUCTURE: 97% COARSE PEARLITE AND 3% FERRITE
07 COMM NOTE: TRACES OF TITANIUM NITRIDES & SULFIDE INCLUSIONS
08 COMM HEAT AFFECTED ZONE: PLATE MARTENSITE WITH 30-35% RETAINED AUSTENITE
09 COMM AND MASSIVE CHILL CARRIDES ALONG THE FUSION LINE.
10 MICR FILE:1537
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018106 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
 LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
 A0018106 10/24/90 A60 TEST BLOCK E08A
 HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
 0000000000 N.I.U. 0000000000
 BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
 0 0 N.I.U. DISPOSITION DATE 11/13/90 M 6
 DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90
 COMMENT FOR INFORMATION
 SUBMISSION COMMENTS WELD SAMPLE
 TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/12/90 TECH INITIALS LIT
 TEST SUMMARY
 SAMPLE PREP COMPLETED
 TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/12/90 TECH INITIALS LIT
 01 COMM #1 #2 #3
 02 COMM WELD >RC70 >RC70 >RC70
 03 COMM FUSION LINE RC47 RC60 RC60
 04 COMM H.A.Z. RC58 RC61 RC63
 05 COMM BASE PLATE = RB86
 TEST NAME 09 MICRO DATE COMPLETED 11/12/90 TECH INITIALS LIT
 01 COMM BASE PLATE: GRAY IRON
 02 COMM GRAPHITE TYPE: A
 MORE SCREENS FOR THIS LAB PAPER NEXT TRAN (-)
 A0018106 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
 03 COMM GRAPHITE SIZE: 3
 04 COMM CARBIDES: NIL
 05 COMM STEADITE: 41%
 06 COMM STRUCTURE: 97% COARSE PEARLITE AND 3% FERRITE
 07 COMM NOTE: TRACES OF TITANIUM NITRIDES & SULFIDE INCLUSIONS
 08 COMM HEAT AFFECTED ZONE: PLATE MARTENSITE WITH 30-35% RETAINED AUSTENITE
 09 COMM AND MASSIVE CHILL CARBIDES AT THE FUSION LINE.
 10 MICR FILE: 1538
 LAST SCREEN FOR THIS LAB PAPER NEXT TRAN (-)

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A0018108 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018108 10/24/90 R20 TEST BLOCK B08A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
0000000000 N.I.U. 00000000000
BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. M 5
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/13/90 TECH INITIALS LIT
TEST SUMMARY

SAMPLE PREP COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/13/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD RC70 RC63 RC70
03 COMM FUSION LINE RC56 RC45 RC58
04 COMM H.A.Z. RC63 RC58 RC63
05 COMM BASE PLATE = RB88

TEST NAME 09 MICRO DATE COMPLETED 11/13/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN (
A0018108 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM TRACES OF TITANIUM NITRIDES & SULFIDE INCLUSIONS
07 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
08 COMM HEAT AFFECTED ZONE: MARTENSITIC STRUCTURE WITH 30-35% RETAINED
09 COMM AUSTENITE AND THERE ARE MASSIVE CHILL TYPE CARBIDES AT
10 COMM THE FUSION LINE.
11 MICR FILE:1593
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN (

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A0018110 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018110 10/24/90 R30 TEST BLOCK R08A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
000000000000 N.I.U. 000000000000
BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U.
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90 M 6
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/13/90 TECH INITIALS LIT
TEST SUMMARY

SAMPLE PREP COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/13/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD NO TEST >RC70 RC70
03 COMM FUSION LINE NO TEST RC50 RC56
04 COMM H.A.Z. RC60 RC62 RC64
05 COMM BASE PLATE = RB86

TEST NAME 07 MICRO DATE COMPLETED 11/13/90 TECH INITIALS LIT
01 COMM BASE PLATE = GRAY IRON
02 COMM GRAPHITE TYPE: "A"
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018110 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM TRACES OF TITANIUM NITRIDES & SULFIDE INCLUSIONS
07 COMM STRUCTURE: 97% COARSE PEARLITE AND 3% FERRITE
08 COMM H.A.Z. #1: MARTENSITIC MATRIX WITH 20% RETAINED AUSTENITE
09 COMM #2&3: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE
10 COMM AND MASSIVE CHILL CARBIDES ALONG THE FUSION LINE & WELD.
11 MICR FILE: 1544
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018111 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
 LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
 A0018111 10/24/90 R40 TEST BLOCK H084
 HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
 0000000000 N.I.U. 0000000000
 BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
 000001 003 N.I.U. 4
 DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/13/90 6
 COMMENT FOR INFORMATION
 SUBMISSION COMMENTS WELD SAMPLE
 TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/13/90 TECH INITIALS LIT
 TEST SUMMARY
 SAMPLE PREP COMPLETED
 TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/13/90 TECH INITIALS LIT
 01 COMM #1
 02 COMM WELD #2
 03 COMM FUSION LINE RC670 RC69 NO WELD #3
 04 COMM H.A.Z. RC61 RC66 NO TEST
 05 COMM BASE PLATE = RB86 RC62 RC64 RC60
 TEST NAME 09 MICRO DATE COMPLETED 11/13/90 TECH INITIALS LIT
 01 COMM BASE PLATE: GRAY IRON
 02 COMM GRAPHITE TYPE: A
 MORE SCREENS FOR THIS LAB PAPER
 A0018111 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
 03 COMM GRAPHITE SIZE: 3 NEXT TRAN ()
 04 COMM CARBIDES: NIL
 05 COMM STEADITE: 1%
 06 COMM STRUCTURE: 97% COARSE PEARLITE
 07 COMM 3% FERRITE
 08 COMM TRACE OF TITANIUM NITRIDES & SULFIDE INCLUSIONS
 09 COMM H.A.Z. STRUCTURE: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE
 10 COMM AND MASSIVE CHILL CARBIDES ALONG THE FUSION LINE & WELD.
 11 COMM NOTE: NO WELD DEPOSITS ON SAMPLE #3
 12 COMM FILE: 1546
 LAST SCREEN FOR THIS LAB PAPER
 NEXT TRAN ()

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A0018112 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018112 10/24/90 B60 TEST BLOCK B084
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
0000000000 N.I.U. 0000000000
BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. M 6
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/14/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED / / TECH INITIALS
TEST SUMMARY

SAMPLE PREP COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM #1
02 COMM WELD >RC70 >RC70 >RC70
03 COMM FUSION LINE RC57 RC48 RC48
04 COMM H.A.Z. RC62 RC63 RC61
05 COMM BASE PLATE = RB86
TEST NAME 09 MICRO DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018112 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
07 COMM INCLUSIONS: SULFIDE & TITANIUM NITRIDES
08 COMM H.A.Z. STRUCTURE: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE
09 COMM AND CHILL CARBIDES AT THE FUSION LINE & WELD
10 MICR FILE: 1547
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018113 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018113 10/24/90 C20 TEST BLOCK H086
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
0000000000 N.I.U. 0000000000
BLD AREA LOT-SZ 1ST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. M 5
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/14/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/14/90 TECH INITIALS LIT
TEST SUMMARY

SAMPLE PREP COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD RC69 RC65 RC64
03 COMM FUSION LINE RC57 RC50 RC60
04 COMM H.A.Z. RC61 RC62 RC62
05 COMM BASE PLATE = RB86
TEST NAME 09 MICRO DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018113 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM INCLUSIONS: SULFIDE & TITANIUM NITRIDES
07 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
08 COMM H.A.Z. STRUCTURE: MARTENSITIC MARIX WITH 30-35% RETAINED AUSTENITE
09 COMM AND MASSIVE CHILL CARBIDES ALONG THE FUSION LINE & WELD.
10 NICK FILE: 1550
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018114 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018114 10/24/90 C30 TEST BLOCK B08A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
000000000000 N.I.U. 000000000000
ELD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. M 6
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/14/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/14/90 TECH INITIALS LIT
TEST SUMMARY

WORK COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD RC65 RC67 RC64
03 COMM FUSION LINE RC60 RC61 RC50
04 COMM H.A.Z. RC61 RX61
05 COMM BASE PLATE = RB87
TEST NAME 09 MICRO DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018114 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
03 COMM GRAPHITE SIZE: 3
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM INCLUSIONS: SULFIDE & TITANIUM NITRIDE
07 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
08 COMM H.A.Z. STRUCTURE: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE
09 COMM AND MASSIVE CHILL CARBIDES ALONG THE FUSION ZONE.
10 MICK FILE:1554
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018115 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018115 10/24/90 C40 TEST BLOCK B03A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
000000000000 N.I.U. 000000000000
ELD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U.
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/14/90 M 6
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM COMPLETED
TEST NAME 05 CORE HARDNESS DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM #1
02 COMM WELD NO WELD RC66 RC67
03 COMM FUSION LINE NO TEST RC53 RC53
04 COMM H.A.Z. RC61 RC64 RC62
05 COMM BASE PLATE = R886
TEST NAME 09 MICRO DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
03 COMM GRAPHITE SIZE: 3
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018115 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
04 COMM CARBIDES: NIL
05 COMM STEADITE: 1%
06 COMM INCLUSIONS: SUFIDES & TITANIUM NITRIDES
07 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
08 COMM H.A.Z. STRUCTURE:
09 COMM #1: MARTENSITE WITH 20% RETAINED AUSTENITE
10 COMM #2&3: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE AND
11 COMM MASSIVE CHILL CARBIDES ALONG THE FUSION ZONE.
12 MICR FILE: 1555
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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A0018116 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
LAB-NO DATE-RECD PART-NO. PART DESCRIPTION ONE-E-SPEC LAB-CODE
A0018116 10/24/90 C60 TEST BLOCK B08A
HEAT-NO SHEET-NO SUPPLIER #/NAME SUPP-CD LOAD-NO TRAFFIC-NO
0000000000 N.I.U. 0000000000
BLD AREA LOT-SZ TST-SZ SUBMITTED BY EXT# DEPARTMENT-NAME M/N DIS AUD
000001 003 N.I.U. DISPOSITION DATE 11/14/90 M 6
DISPOSITION BY SUPERVISOR LIT DISPOSITION DATE 11/14/90
COMMENT FOR INFORMATION
SUBMISSION COMMENTS WELD SAMPLE
TEST NAME 01 SAMPLE PREPARATION DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM COMPLETED
TEST NAME 06 CORE HARDNESS DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM #1 #2 #3
02 COMM WELD )RC70 RC64 )RC70
03 COMM FUSION LINE RC57 RC55 RC50
04 COMM H.A.Z. RC62 RC63 RC62
05 COMM BASE PLATE = R086
TEST NAME 09 MICRO DATE COMPLETED 11/14/90 TECH INITIALS LIT
01 COMM BASE PLATE: GRAY IRON
02 COMM GRAPHITE TYPE: A
03 COMM GRAPHITE SIZE: 3
MORE SCREENS FOR THIS LAB PAPER NEXT TRAN ( - )
A0018116 CATERPILLAR MET LAB A-PAPER SYSTEM - INQUIRY SCREEN
04 COMM CARBIDES: 3
05 COMM STEADITE: 1%
06 COMM STRUCTURE: 97% COARSE PEARLITE & 3% FERRITE
07 COMM H.A.Z. STRUCTURE: MARTENSITIC MATRIX WITH 30-35% RETAINED AUSTENITE
08 COMM AND MASSIVE CHILLED CARBIDES ALONG THE FUSION ZONE
LAST SCREEN FOR THIS LAB PAPER NEXT TRAN ( - )

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Appendix B
Results of the X-Ray
Diffraction Examination

Northern Illinois University
X-ray Spectroscopy Department of Geology
1976-1981

Appendix C
Stress Analyses of
the Samples