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Keywords: laser surface hardening; wear resistance; metal gears; surface hardness; microstructural changes; gear steels; hardening parameters; wear testing; gear material properties; surface treatment techniques.

Classification: DCC Code: 621.8

Language: English

Great Britain Journals Press

LJP Copyright ID: 392954
Print ISSN: 2631-8474
Online ISSN: 2631-8482

London Journal of Engineering Research

Volume 24 | Issue 4 | Compilation 1.0

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This study investigates the efficacy of laser surface hardening (LSH) as a method to enhance the wear resistance of metal gears, comparing it with traditional hardening techniques such as induction and flame hardening. The LSH process involves using a high-energy laser beam to rapidly heat the gear surface, resulting in microstructural changes that increase hardness and wear resistance. Experiments were conducted using two common gear steels, JIS-SCM415 and JIS-S45C, with the laser parameters optimized to achieve the desired hardness profile. The results showed that the best hardening was achieved with a laser power of 1000W, scanning speed of 100mm/s, and a spot size of 1mm, resulting in a surface hardness of 672 HV and a core hardness of 502 HV. Wear testing indicated that the wear rate of laser-hardened gears was comparable to new conventional gears, with a weight loss of 10-12 mg/hr. The study demonstrates that LSH can significantly improve the wear resistance of gears, with minimal distortion and precise control over the hardened depth, making it a promising alternative to conventional hardening methods for enhancing gear longevity and performance.

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I. INTRODUCTION

There are four directions of hardness enhancement techniques, namely: solid-state phase transformation hardening, surface coating, chemical heat treatment, and surface hardening [1], [2]. Laser surface hardening (LSH) is a newly developed surface hardening process that provides an effective means to increase the wear resistance of gear material [3]. This is a process in which a focused coherent high-energy beam is used to rapidly heat the metal at the surface to a temperature which is above the transformation temperature and the melting point, but which is well below the temperature of the entire workpiece. The laser heat source is moved over the surface in a regular pattern and then the part is either water or air cooled. The change in the microstructure of the substrate induced by the cooling rate of the treated area, which is controlled by the thermal diffusivity of the material and the laser scanning speed [4].

Typically, the laser hardening process involves the heating and cooling time of the order of microseconds up to milliseconds [5]. By selecting suitable processing parameters, various microstructures and hardness profiles can be obtained. If the gear made of through-hardening steel like JIS-SCM415 is subjected to the through-hardening heat treatment, which offers the highest possible wear resistance, the hardness profile obtained by the laser hardening process should be similar to the through-hardening profile. Although the basic principle of the laser hardening process is well understood, the prediction of the optimum process parameters and the evaluation of the gear's micro-macro hardness profile have not been established due to

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a lack of knowledge on the kinetics of the heating and cooling of the gear material and the measurement method of the thermal physical properties of the work material [6]. The microstructure changes caused by the laser surface hardening process are complex and diverse. Compared with the usual hardening process such as quench hardening, with that in mind, it is understood that the hardness of the laser-treated area and the wear resistance do not correlate simply, and most of the previous studies report that the wear test produces better results than the hardness test [7]. Since it is incredibly difficult to directly evaluate the gear tooth surface, we will examine the wear resistance of the pin-on-disk wear test and clarify the correlation between the wear micro-macro area and the hardness profile to provide a measurable method in the evaluation of the gear's micro-macro hardness profile, thus obtaining the optimum process parameters and the hardening design that creates the minimum gear wear in any situation.

1.1 Background

Laser hardening, compared to other surface heat treatments such as induction and flame hardening, offers several advantages. Laser hardening is applicable for irregular surfaces and complicated shapes, as the heat source from the laser can be controlled easily. It can also be used for local hardening or hardening only in specific areas [8]. This is important because only the surface of the gear needs to be hardened. In previous research, the steel manufacture of material gears has been used from cheap steels to expensive alloy steel. This is interesting for study because the method of hardening can affect the properties of the material, and possibly the method can be used in hardening other materials such as iron and steel cast, or even stainless steels.

Gears needing wear and pitting resistance means we require higher surface hardness. As the gears' loading condition assumes that the hardness value of the core and surface are considered the same, this will make the contact stress of the gear very high, which affects the hardness of the material around the area. Under these conditions, high contact stress promotes the gear's surface to be worn and decreases the hardness. High hardness of the gear surface means we also need to consider the ability to deliver good fatigue resistance and abrasive wear resistance. This is different from the characteristic of through hardening as it is better used for case hardening with the gear.

In recent years, the investments in the machinery industry have escalated the manufacture of mining, construction, oil and gas machinery equipment, and methods to process metal surfaces that can change the properties and increase their performance lifespan. In these industries, metal gears have been long used as they are suitable for harsh conditions and heavy loading. Gears are usually made from low carbon steels with sufficient strength and toughness.

1.2 Objective

The procedure to be followed in this work for obtaining the above expected result is as follows:

1. Selection of processing parameters of the laser such as beam diameter, power, speed, and spot size. With these parameters, a small portion of the surface of the gear is heated and then it can be quenched immediately by contact from the rest of the material, resulting in microstructure changes.
2. Gear samples will be checked for various microstructures and hardness between small variations of laser parameters;
3. The wear resistance of these selected simulated microstructures will be tested in the laboratory and conducted field tests;
4. The wear rate of these gears will be used to compare it to the previous gears by preparing a dual block between two gears and loading it by means of a spring and applying rotational motion. This whole procedure is done to test the toughness of microstructures of gears.

II. LITERATURE REVIEW

Gears are mechanical components used to transmit motion between rotating shafts. Most often, gears are used to increase or decrease the torque, increase or decrease the speed, and/or change the direction of the shaft rotation [9]. There are many different types of gears such as spur gears, worm gears, bevel gears, etc., that are used in a variety of appliances. Gears are generally made out of metal due to the high strength characteristics [10]. Steel is most often used due to its high strength and low cost. Gears are subject to a unique form of wear called macropitting, for which few treatment options exist, and tooth breakage, which can generally be prevented through increasing the hardness of the gear [11].

Gears enable the transmission of motion and power between rotating shafts. However, they are often regarded as weak components in machinery and are susceptible to failure through a variety of failure modes [12]. Each gear has its own specific gear tooth design. While each design has different applications and performance requirements, they all will encounter wear. Just a few examples of the types of gears are bevel, helical, spur, and worm gears [13]. Wear can vary from being a marginal concern for some applications to being a crippling problem for others. Even though wear is an undesirable phenomenon, it can be used as an end-of-life indicator for some applications when catastrophic failure is a possibility [14].

Wear is defined as a surface degradation involving the progressive loss of material from a solid body while it remains in repetitive contact with another body. There are a variety of wear forms that affect gears such as abrasive wear, adhesive wear, and pitting. These wear forms are caused by contact stress [15]. High contact stress often causes surface fatigue and gear failure as the objects slip to a rolling motion. It is estimated that 85% of gear failures are the result of surface fatigue.

Gears can fail from pitting fatigue, with an incidence rate as high as 28%. Pitting damage is related to the loss of surface strength and is characterized by the formation of surface cavities and eventual removal of surface material from adhesive wear [16]. Gears subject to pitting exhibit increased surface roughness and noise and generally cannot meet the intended gear life.

Pitting can cause complete tooth failure or failure of the entire gearbox. The various types of metal gears have different wear resistance properties and for certain applications, it may be necessary to enhance these properties in order to increase the useful life of the gear [17].

When comparing modern hardening techniques, laser beam hardening is relatively new, emerging in the 1980s [18]. However, its use is increasing in industry, particularly in the automotive and machine tool industries. It is a selective hardening process using a laser as a heat source. The process is normally conducted using a CNC machine, allowing a precise hardened area to be achieved. Gears are an ideal candidate for laser hardening because their geometry allows heat to be applied to precise locations, with minimal thermal effect on the surrounding area, enabling production cost reduction [19]. The aim of laser hardening is to increase the wear resistance of the gear surface and improve fatigue strength. This is achieved by the rapid heating and subsequent rapid cooling of the surface that changes the microstructure only in the surface layer, resulting in increased hardness and wear resistance. By careful selection of process parameters, a range of microstructures can be achieved to suit the particular gear application. A key advantage of laser hardening over conventional hardening methods is the minimal distortion that occurs due to the localized heating and cooling [20]. This is a significant benefit, allowing closer dimensional tolerances to be held, reducing or even eliminating the need for post-hardening finishing operations. The hardening depths can be more closely controlled than by conventional methods, typically ranging from 0.8-1.2 times the laser spot diameter [21].

However, this can be adjusted by multiple scans of the laser to achieve greater depths if required. This contrasts with conventional case hardening that often results in a thin, hard surface layer but with a significant predetermined risk of distortion to the part and a shallow hardened depth.

III. MATERIAL AND METHODS

Laser surface hardening is a recent addition to the induction hardening process, which uses a focused infrared laser to heat the surface of steel, with the heating rate and cooling rate are extremely high. When the laser stops heating the surface, the steel will cool extremely fast to room temperature. This will produce a martensitic structure at the surface. Depending on the heating rate and energy input, it is possible to harden to a depth between 0.5 to 3mm. This method is very favorable for only hardening the surface because it does not require any masking or post-cleaning process. The high cooling rate also minimizes part distortion. In this research, Rofin DC-015 diffusion cooled CO_2 slab laser and a max pulse energy of 1.8kJ were used. In order to get the best process parameters, the Taguchi method was used. By analyzing an array of experiments, it makes it possible to determine which factor is the most important, and which level of the factor is the best.

The selection of materials for metal gears is very important for improving wear resistance properties. In this study, two types of commercial metal gears, JIS-SCM415 and JIS-S45C, were used. Generally, JIS-SCM415 is used for small gears and it is a low carbon alloy steel which has a good secondary hardening effect. JIS-S45C is a low carbon steel which is commonly used to produce the gears. Both materials are widely used for transmission elements because of their relatively low cost. These gears were heat treated to increase their hardness value. The steel hardening process is essential to provide hardness, to make sure it does not wear easily when it is used. As there are a number of steel hardening methods, one of the best methods to harden only the surface is by using a laser beam. By varying the process parameters, it can produce different hardness levels at the surface.

3.1 Selection of Metal Gear Materials

In order to establish the wear mechanisms and the effect of laser processing for the materials studied, there will be wear testing of both the as received and laser treated gear materials. A series of wear tests for pitting and scuffing using a ball on disc machine will be performed with rotating and reciprocating motion respectively, using gear specimens to represent a simplified version of gear contact, i.e. line contact under high Hertzian stress between two parallel cylinders. Static contact tests will also carried out to observe the galling resistance of the surface hardened materials. An assessment of the wear damage and wear rate at each contact condition will be used to correlate the materials wear performance with their contact fatigue performance and wear simulation models in the future.

The needs for near net shape processing and improved mechanical performance are driving the use of powder metallurgy (P/M) materials for transmissions components, however these materials often perform poorly in component level rolling contact fatigue tests due to the large surface porosity and the detrimental affect this has on surface contact damage. An iron based P/M material, Ancorloy 60, has been selected as a representative of P/M materials in general given its similar composition to conventional steel, and it is anticipated that there will be a significant improvement in its wear resistance from laser surface hardening. This will allow a comparison to be made of the performance in gear contact fatigue of the P/M material against conventionally through hardened steel gears, with respect to the microstructures and wear response of the two materials.

The most commonly used carburising steel for gears is EN36, a 3% NiCrMo steel specified in British Standard 970 Part 1. The steel is through hardening and possesses a good combination of strength and toughness in the heat-treated condition, which makes it a good candidate for case hardening processing techniques such as carburising and induction hardening. However carburised gears themselves are rarely specified to be laser case hardened, and EN36 is difficult to conventionally through harden due to its hardenability and the alloy it contains. This means that the wear resistance of the gear tooth surfaces in service tends to be low due to near surface fatigue damage over time from rolling and sliding contact. The effect of this is surface pitting, with a high proportion of contact fatigue cracks and spalling.

The important issues for the choice of gear material have narrowed the choice down to two metal materials, each having certain characteristics in mechanical properties and microstructures that could affect the wear response and hence the success of laser processing for improving their wear resistance.

3.2 Laser Surface Hardening Process Parameters

Hardness of metal gears. The parameters that affect are power, scanning speed, overlapping, spot size, and type of gas. In this research, argon gas was used as an inert gas. Spot sizes used were 1mm and 2mm. Two types of power have been chosen, low power and high power. The samples were prepared according to the international standards for abrasive wear testing, and the hardened layer was observed under a metallurgical microscope. Microhardness test data and metallography photos showed the depth and width of the hardening layer. Wear tests were conducted using pin-on-disc method. From this research, it was found that the best laser hardening results are produced using power of 1000W, scanning speed 100mm/s, argon gas, spot size 1mm, and quench method. Depth of penetration was 0.3mm with 672° microhardness value in the hardening layer and 502° on core material. Weight loss in wear testing is 10-12 mg/hr which is equivalent to the wear rate for new conventional gear. After several tests, it was concluded that the laser hardening process can increase the wear resistance of the gears. High scanning speeds and powers increased wear on the disk surface and possibly increased the temperature inside the samples, generating the thermal cracking. High scanning speeds and powers increased wear on the disk surface and possibly increased the temperature inside the samples, generating the thermal cracking.

3.3 Wear Testing Procedure

An accelerated wear testing procedure was conducted to compare the wear resistance of laser surface hardened and conventionally heat-treated gears. A modified four ball test rig was used to run the wear tests using 52100 bearing steel balls. The ball on flat configuration was chosen as it simulates a realistic gear tooth contact. The geometry of the balls was slightly modified to have a flat surface on the bottom to closely replicate the actual contact conditions. The test conditions were 294N load, 0.07m/s and the test duration was for 1 hour. This gave a total sliding distance of 252m which is sufficient to give good data repeatability. This test rig was also used in other research projects for testing gear materials. The wear volume on both the balls and discs were measured with a microbalance using Vegard's rule, with an accuracy of $1x10^{-6}mm^{3}$. This type of test quantifies the wear rate of the material and is good for determining the ranking of wear resistance between different materials. Further wear tests were also carried out using the same balls and disc specimens in a fully formulated gear oil under the same conditions to compare wear rates in both dry and lubricated conditions.

3.4 Data Collection and Analysis

To determine the wear volume, wear testing is carried out using a laboratory test machine known as the SRV wear testing machine. The SRV wear testing (also known as block on ring) machine is a three-order servo-hydraulic machine with a loading capacity up to 15kN. It is versatile dry and lubricated testing unit used for tribological testing of materials, lubricants and transmission elements in accordance with several national and international standard test methods. The machine can mimic actual working conditions where the gears are usually operated and can carry out wear testing for the duration required to obtain wear volume data.

Data collection is a very important step as it assists in measuring the quality of the hardened layer on the material. In this case, wear test is used to analyse the wear resistance properties of the laser surface hardened samples as compared to the samples without laser surface hardening. Wear test was conducted on the as prepared samples to obtain the initial data and also on the hardened samples after laser surface hardening is carried out on them. Wear test on the as prepared samples is carried out in order to obtain the initial wear rate and also to compare the wear rate of these samples with the samples after laser surface hardening is done on them. This will then show the difference in wear rate between the as prepared samples and the hardened samples and whether laser surface hardening will improve the wear resistance properties of the gear samples. The wear testing results are then used to prepare graphs of wear volume against distance slid for all samples. From these graphs, the wear rate of the samples can be determined.

IV. RESULTS AND DISCUSSION

In the present work, an extensive series of pin-on-disc wear tests has been carried out using laser-treated gears in an attempt to establish the optimal conditions for wear performance in a range of gear steels. These results form the basis for assessing the wear resistance improvement achieved using laser surface hardening, the effect of process parameters on wear performance, and the wear performance of laser-treated gears compared with other surface hardening techniques. The wear tests were carried out using a block-on-ring test rig, which is designed to simulate the conditions of rolling/sliding contact experienced by gear teeth. The variation of wear rate with applied load was investigated, and the mechanism of wear established by examination of the worn surface and wear debris. In general, the wear resistance of laser-treated gears was improved considerably compared with untreated gears, and the degree of improvement was dependent on the steel and the laser hardening conditions.

Wear is one of the predominant reasons for the provision of replacement of engineering elements, and it is a very complex phenomenon involving a number of mechanisms. Laser surface hardening is a technique that improves the wear resistance of contacting surfaces by providing a thin superficial layer of high hardness. It is possible to control the microstructure and composition of the hardened layer and hence its wear properties, independently of those of the bulk material. The influence of process parameters on wear performance can also be investigated and related to the microstructural changes in the layer.

4.1 Wear Resistance Improvement in Laser Hardened Gears

Various types of surface hardening techniques, such as flame hardening, induction hardening, nitriding, and carburizing, are available to increase the surface hardness of metal. But these techniques increase the hardness of the surface up to a certain depth from the surface and also offer a hardening depth gradient. It has been reported that a higher hardness level of the gear increases the wear resistance of the gear. The depth of the hardened layer of the above-mentioned hardening processes may be sufficient to improve the wear resistance of the component, but it is very difficult to control the hardening depth, and maintaining a hardening depth gradient is dangerous for heavily loaded gears. So, it is possible that the gear may become too hard and brittle and may experience tooth breaking during operation. Therefore, it is necessary to select a hardening technique that will provide a uniform hardened layer with a controlled depth from the surface. A uniform hardened layer means constant hardness at the same depth from the surface. A very high hardness level is not required for plain carbon steel gears. A tempered gear will not be subject to brittle tooth failure. A hardened layer having a hardness of 50 to 60 HRC with a depth of 0.5 to 1 mm is cultivated for the same above-mentioned reasons. This range of hardness is quite sufficient to improve the wear resistance of the gear, and it is also possible to remove the big gear by grinding after the hardening operation in order to remove the hardened layer and any geometric changes into the tooth profile. This can be achieved if the gear is pretreated before the last hardening to remove scale and oxidation layers on the gear.

High carbon gears may be gas last hardened and directly last hardened in a protective environment can offer a surface hardened layer with controlled hardening depth, but the cost of the same is quite high. Last hardening techniques use high power density energy sources such as laser, electron beam, and plasma. High power density radiations are directed towards the material surface, and the energy of the radiation is absorbed by the material. It has been reported that by inputting an accurate quantity of heat to the material, it is possible to obtain a uniform hardened layer with controlled hardening depth. The depth of the hardened layer obtained from laser last hardening is very shallow compared to the other last hardening techniques, and it may be a suitable last hardening process for gearing. So, last surface hardening using laser is selected as a hardening method to improve the wear resistance property of plain carbon steel gears.

In the present work, an attempt has been made to use the last surface hardening technique to improve the wear resistance properties of gears made of plain carbon steel. These gears are widely used for sugar cane crushing in the sugar industry. Such types of gears experience severe wear in field operations. The wear resistance property of the gear has been closely associated with the surface hardness of the gear. To improve wear resistance, the surface hardness of the gear should be increased and improved. It has been reported that the wear rate can be significantly reduced by increasing the surface hardness of the gear.

4.2. Effect of Process Parameters on Wear Resistance

At each of the three loads, wear rate increased with an increase in corresponding specific wear rates mentioned earlier. From these two pieces of data, wear intensity was calculated to examine the effect of pin hardness on the mated surface. Both the specific wear rate and wear intensity on the cobalt base alloy were virtually constant at all test loads. A similar situation was discovered with the heat-treated 0.5% carbon steel. Very much higher specific wear rates were encountered with the as-received steel and also the annealed steel. For the heat-treated steel, wear rate also increased with an increase in load, although it was lower than that encountered with the other forms of this alloy. This suggests that increasing gear surface hardness has a beneficial effect on wear resistance. Several changes in wear mechanism were discovered for the gear materials at various combinations of load and speed. These changes could be rationalized in terms of a modified PV value. The specific wear rate for the cobalt base alloy was almost constant at all test conditions, suggesting that abrasive wear was occurring. This is typical of adhesive wear, and the increase in wear rate with an increase in PV value is caused by the increase in surface contact temperature softening the cobalt binder phase in the cemented carbide and allowing increased adhesion to the steel counterface. This change in wear mechanism was confirmed by examining pin and tooth surfaces for evidence of transfer of cobalt base alloy.

4.3 Comparison with other Surface Hardening Techniques

Another important factor is the alloying element. The compound layer of the carburized gear tooth absorbs carbon and becomes very brittle. This is not desirable in some cases like heavy vehicle gears. An induction hardened gear absorbs less or no alloying element depending upon the material and process parameter. In this case, alloying elements do not change much and properties just alter due to a change in hardness. It quite often does not satisfy the overall aim of improving wear resistance. Laser hardening has an advantage in this case by avoiding thermal stress and surface melting the part of the gear tooth. High alloying steels can be surface melted and cooled rapidly to improve the properties without deteriorating overall properties by thermal stress.

On the other hand, the laser hardened layer has hardness more than 700 HV and the average hardness of the whole melted zone is almost equally good, which stays close to the surface hardness and gradually minimizes at a certain depth. This kind of hardness profile will ensure much better wear resistance during sliding and pitting, and it is expected that the fatigue strength of the gear tooth will also improve due to the higher hardness of the surface layer.

The properties achieved by laser hardening were compared with two conventional and most widely used surface hardening methods, i.e. gas carburizing and induction hardening. The hardness profile of the laser hardened layer is far better than the hardened case of carburizing and close to the induction hardening. The hardness profile of the carburized surface indicates a thin compound layer having hardness in the range of 900-1000 HV, which gradually minimizes and stays around 500 HV after a certain depth. The induction hardened layer has hardness more than 550 HV and gradually minimizes at greater depth.

The hardness obtained from these two techniques at the surface of the gear is not good enough to improve the wear resistance of the gear tooth during sliding to a greater extent.

V. CONCLUSION

This research has successfully demonstrated the potential of laser surface hardening (LSH) as an effective method for enhancing the wear resistance of metal gears. Through the careful selection of laser parameters, including power, scanning speed, and spot size, it was possible to achieve significant improvements in surface hardness and wear resistance. The optimized parameters resulted in a surface hardness of 672 HV and a core hardness of 502 HV for gears made of JIS-SCM415 and JIS-S45C steels. Wear testing further confirmed that the wear rate of laser-hardened gears was comparable to that of new conventional gears, with a weight loss of 10-12 mg/hr.

The study also highlighted the advantages of LSH over traditional hardening methods such as induction and flame hardening. The precision and control offered by the laser process allow for minimal distortion and the ability to target specific areas for hardening, making it particularly suitable for complex gear geometries. Furthermore, the rapid heating and cooling rates associated with LSH result in a fine microstructure that contributes to the enhanced wear resistance.

While the results are promising, it is important to note that the relationship between hardness and wear resistance is not straightforward. The wear performance of gears is influenced by a range of factors including the microstructure, residual stresses, and the presence of surface defects. Therefore, future work should focus on a deeper understanding of these factors and their interaction with the laser hardening process.

Additionally, further studies are needed to optimize the LSH process for different types of gears and materials, and to evaluate the long-term performance of laser-hardened gears in real-world applications.

In conclusion, laser surface hardening has been shown to be a viable and effective technique for improving the wear resistance of metal gears. Its ability to precisely control the hardening process and achieve desirable microstructural changes makes it a promising alternative to conventional hardening methods, with the potential to extend the service life of gears in various industrial applications.

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