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The influence of laser hardening on wear in the valve and valve seat contact

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Abstract

In internal combustion engines it is important to manage the wear in the valve and valve seat contact in order to minimise emissions and maximise economy. Traditionally wear in this contact has been controlled by the use of a valve seat insert and the careful selection of materials for both the valve and the insert. More recently, due to the increasing demands for both performance and cost, alternative methods of controlling the wear, and the resulting valve recession, have been sought.

Using the heating effect of a laser to induce localised phase transformations, to increase hardness and wear resistance, in materials has been used since the 1970s, however it is only in recent years that it has been able to compete with more established surface treatment techniques, particularly in terms of cost, as new laser hardware has been developed.

In this work, a laser has been used to treat the valve seat area of a cast iron cylinder head. In order to optimise the laser parameters for use on the head, preliminary tests were carried out to investigate the fundamental wear characteristics of untreated cast iron and also cast iron with a range of laser treatments. Previous work has identified the predominant wear mechanism in the valve and valve seat contact as impact on valve closure. Two bespoke test machines, one for testing basic specimens and one for testing components, were used to identify the laser parameters most likely to yield acceptable results when applied to a cylinder head to be used in a fired dynamometer test.

Keywords: Wear, Valve, Laser, Hardening.

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1. Introduction

In the valve seat area many impacts and temperature cycles occur over the life of an engine so that the cast iron used to form the cylinder head is not suitable, in its natural state, for the valve seat material. It is critical to maintain the integrity of the valve seating area to ensure that the desired economy and emissions specifications are met. To meet these requirements materials are needed that have, in varying degrees, self lubricating properties, to counteract sliding wear; a relatively high hardness, so that the both parts equally resist wear; and a compressive residual stress on surface to improve fatigue resistance. All of these are easily achievable by laser hardening.

Traditional methods to increase wear resistance include induction hardening and using inserts. Induction hardening gives a homogenous microstructure with good wear resistance [1], but would be expensive to implement on a cylinder head production line due to the slow speed of the process. Using an insert allows tailored materials so different engine variants can have different properties, such as self lubrication. However inserts can be comparatively expensive and increase the complexity of the head by adding components and manufacturing processes.

Using a laser allows microstructual tailoring of the grey cast iron, giving a mixture of graphite flakes, for lubrication, and martensite, for wear resistance. This allows usage of the cylinder head material, removing the need for inserts and reducing piece cost. Laser hardening improves wear resistance and fatigue life [2] and is a very consistent process that allows complex shapes and difficult to access parts to be treated. Due to the size of the laser beam, only a small amount of material is heated, minimising distortion and post hardening machining. The small laser spot size makes the process self quenching, reducing process times and complexity, but cost inefficient for large areas. Metals are highly reflective to laser light and coatings can be used to improve beam absorption, reducing the laser power needed and ensuring process stability. However this adds complexity as the coating needs to be applied and removed after laser hardening. For this application, the short wavelength of the selected laser and the angle of the seat will aid laser absorption, so that an uncoated surface can be used without greatly increasing the laser power needed.

The aim of this work was to study the affect of laser hardening on the wear resistance of cast iron valve seats. Testing was carried out on a specimen impact rig which looked at the effect of the material properties as well as a rig with the valve seat geometry. The latter used valvetrain elements from a current engine and allowed a comparison to be made with the current valve seat inserts. The results from the laser hardened samples were compared with the inserts to decide which laser parameters to use on a running engine. A firing engine test was then performed with the most promising hardening parameters and the result compared with the rig test work. Rig testing was used as a quick, easy and cheap way of testing different laser configurations.

2. Background

Regardless of the continuing development and improvement of internal combustion engines, the wear of components still occurs. The current focus on new materials and processes as a mechanism for cost reduction and light-weighting also means that previously unseen or insignificant problems can appear. This is, of course, true for all components and systems in an engine where contact occurs, but of particular importance, and the scope of this work, is that of the valve, valve seat insert (VSI) and cylinder head contacts.

The environment in which the valves and seat inserts operate is very harsh. During combustion in the cylinder, temperatures on the component surfaces can reach around 500°C. The interface between valve and seat is subjected to an initial impact when the valve closes followed by a second load from the combustion process.

Previous research into valve and VSI wear and subsequent failure has identified three main ways for failure to occur; guttering, torching and recession. Guttering is a corrosive process that occurs at high temperatures and is therefore more common on exhaust valves. It is caused by deposits that are locally welded to the valve surfaces flaking off and taking some valve material with them [3]. Torching is a sudden failure of the valve due to the high temperatures generated by the combustion process ‘burning’ the valve head surfaces, again more common in exhaust valves. Valve recession is the gradual sinking of the valve into the seat insert as a result of material loss due to wear. It is the most common form of failure in inlet valves, where temperatures are not high enough to cause guttering or torching. The oil deposits and combustion products that coat the exhaust valve provide some lubrication in this area and reduce recession to some degree. The major wear mechanisms causing recession are impact wear, arising from the valve striking the seat on closing, and sliding wear, due to the micro-sliding, or slip, at the valve and seat interface as the valve is forced into the seat by the combustion pressure. In most cases, impact wear is the dominating mechanism [4, 5, 6].

With regards to the effect of laser transformation hardening on the wear resistant properties of ferrous metals, there is only a small amount of previous work described in the literature. Pantelis et al. [1] investigated the effects on the wear resistance of CO_2 laser hardened CK60 structural steel and discovered that the process formed martensite in the heat affected zone. This change caused the hardness to increase and improve the resistance to sliding wear. It was also noted that overlapping the laser tracks can temper the martensite and reduce the hardness in that region. The impact wear resistance of a stainless steel was investigated by Tianmin et al. [7] and was found to exhibit improved wear performance after processing. The higher cooling rates that can be achieved with laser hardening, when compared to other heat treatment processes, lead to greater levels of grain refinement and martensite transformation and this is cited as the reason for the improved performance.

3. Experimental Details

3.1. Test Apparatus

Two different types of test apparatus were used in this work. Firstly, a specimen impact wear test rig was used to investigate the fundamental wear characteristics of the materials of interest. Secondly, a test rig that uses production valves and specimens that are geometrically similar to valve seat inserts was used to assess the wear performance of the materials. As two valves are tested simultaneously it is known as the twin valve test rig.

3.1.1. Specimen Impact Wear Tester

The rig is driven and controlled by a 1.1kW electric motor and cam/spring system. The cam is from a production 2.4 litre dual overhead camshaft (D.O.H.C.) diesel engine and acts directly onto a hardened flat present on the arm and is directly opposed by a compression spring. The spring is easily interchangeable to vary the impact energy and closing speed of the striker. The closing velocity can also be varied by changing the clearance between the cam nose and the follower. Although the rig can operate at high speed the actual loads on the cam, spring and bearings are relatively low, so lubrication consists of light grease on the bearings and periodic applications of oil to the cam surface and spring/follower sliding contacts. A schematic of the rig can be seen in Figure 1.

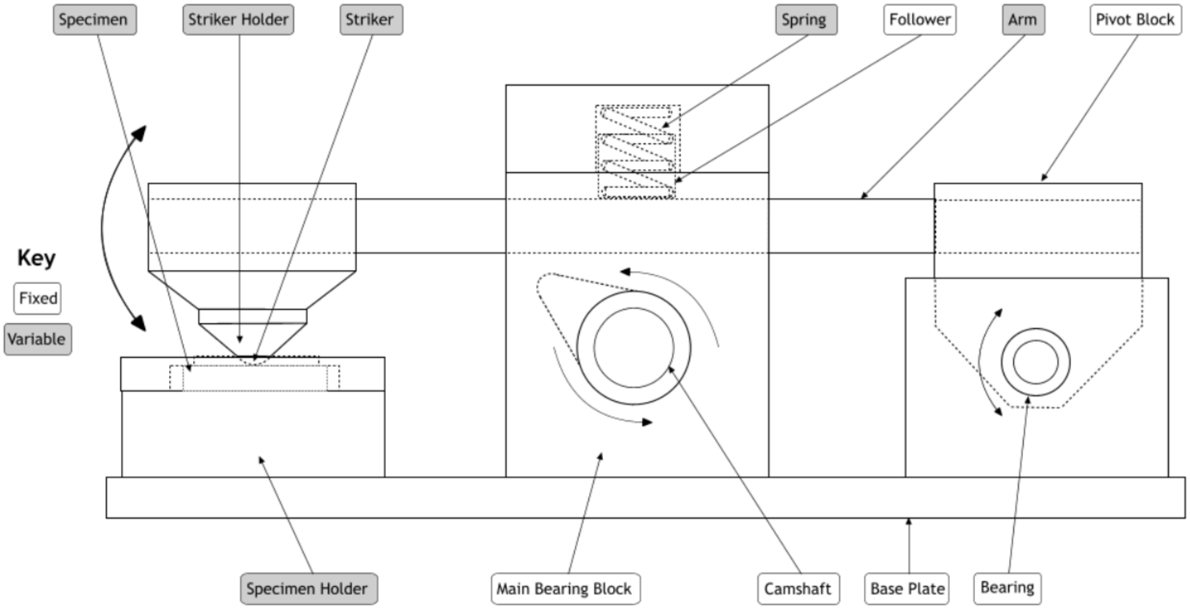

Figure 1. Impact Test Rig Schematic

Throughout this work, a 15mm diameter 400 series stainless steel ball bearing was used as the striker and nominally struck the test specimen at 10Hz. This can be altered by changing the pulley ratios or by using a speed controller. The specimen is retained in position by a two-part specimen holder and is nominally presented normal to the striker.

3.1.2. Twin Valve Test Rig

This test rig, developed for this work, aims to characterise the combined effect of material properties and the geometrical shape it is formed into. This builds on the basic and fundamental material information that can be generated by testing, such as from the specimen impact wear tester, by adding the concept of ‘material pairs’ used for the valve and valve seat insert and, predominately, the effect of the angle between the two seating faces. Other variables such as the level of lubrication, valve closing speed and valve clearance/lash can be also investigated.

Figure 2 shows a schematic of the twin valve test rig. The operating speed of the 2.2kW motor is maintained and varied by a speed controller. The camshaft is located by two rolling element bearings opens the valves directly, via bucket followers, and the valves are closed with valve springs. The bucket followers and valve guides keep the path of the valve true and are mounted underneath and inside the main block.

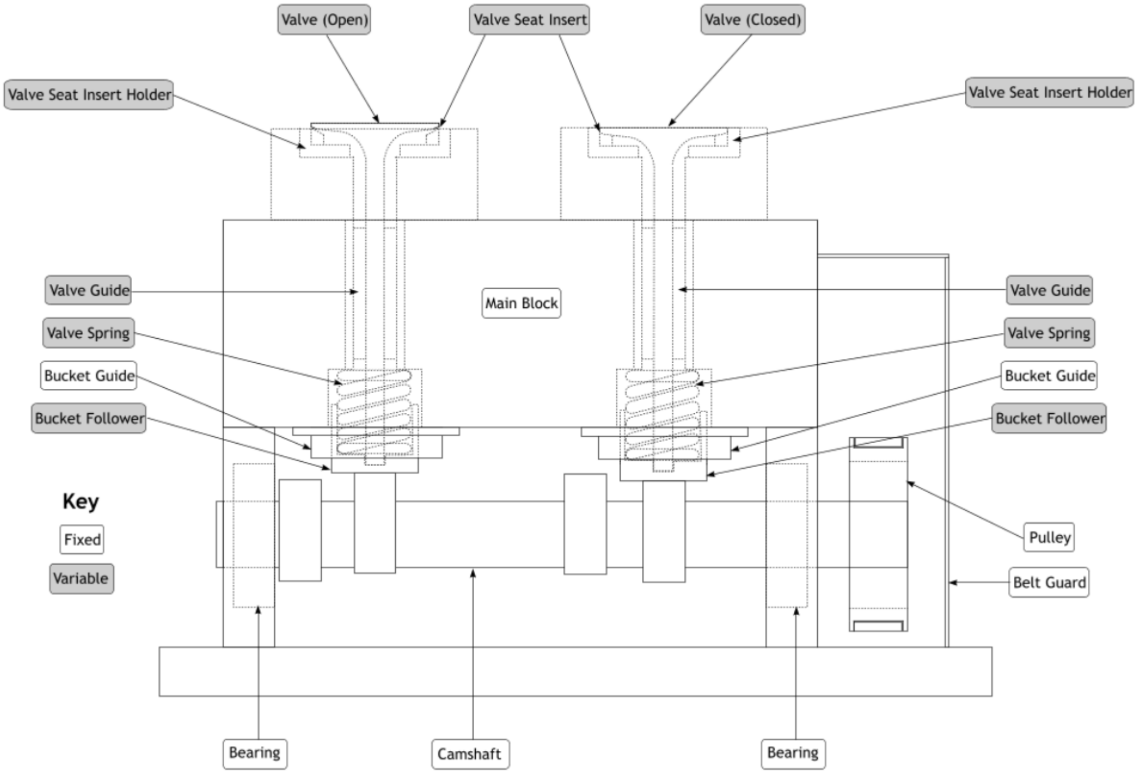

Figure 2. Twin Valve Rig Schematic

The valves and valve seat inserts are held in modules that allow the specimen components to be changed relatively easily. This also allows the inserts to be removed from the rig, without any cutting or grinding, to allow mid-test measurement and enables the inserts to be replaced in the identical orientation after measurement. The valves are allowed to rotate to simulate similar rotations found in engines. The cam/follower contacts are lightly lubricated and no lubricant reaches the valve and valve seat contact.

3.2. Test Specimens

The material used throughout this work was EN-GJL-240 pearlitic grey cast iron. The average hardness was measured to be 195 Hv and the chemical composition is listed in Table 1.

Table 1. Chemical composition of EN-GJL-240 pearlitic grey cast iron

Element	*C*	*Si*	*S*	*Cr*	*Mn*	*Others*	*Fe*
Weight (%)	3.35	2.01	0.08	0.24	0.83	Less than 0.3	Balance

3.2.1. Impact Wear Testing

The samples measured 40mm x 40mm and were cut from 8mm thick cast iron plate. Four sets of specimens were created, three each with a different level of laser treatment and one set was left untreated as a control. The laser treated samples were sprayed with a colloidal graphite spray, Graphit33, to increase the absorption of the laser beam. A 4mm x 4mm square laser spot was run across the middle of the sample using a CO_2 laser operating at 800W. Three different speeds were used: 2, 3.5 and 5 mm/s with the resulting hardness and case depth listed in Table 2. Example laser processed specimens can be seen in Figure 3a, hardened (i.e. Set B and C) and Figure 3b, melted (i.e. Set A).

Table 2. Parameters used and resulting case depth and hardness for impact tests

Specimen Set	***Energy Density (J/mm^2)***	***Speed (mm/s)***	***Melted layer***		***Hardened layer***	
			Depth (mm)	*Hardness (HV)*	*Depth (mm)*	*Hardness (HV)*
Set A	25	2	0.11	890	0.48	655
Set B	14	3.5	No melting occurred		0.38	683
Set C	10	5	No melting occurred		0.29	662

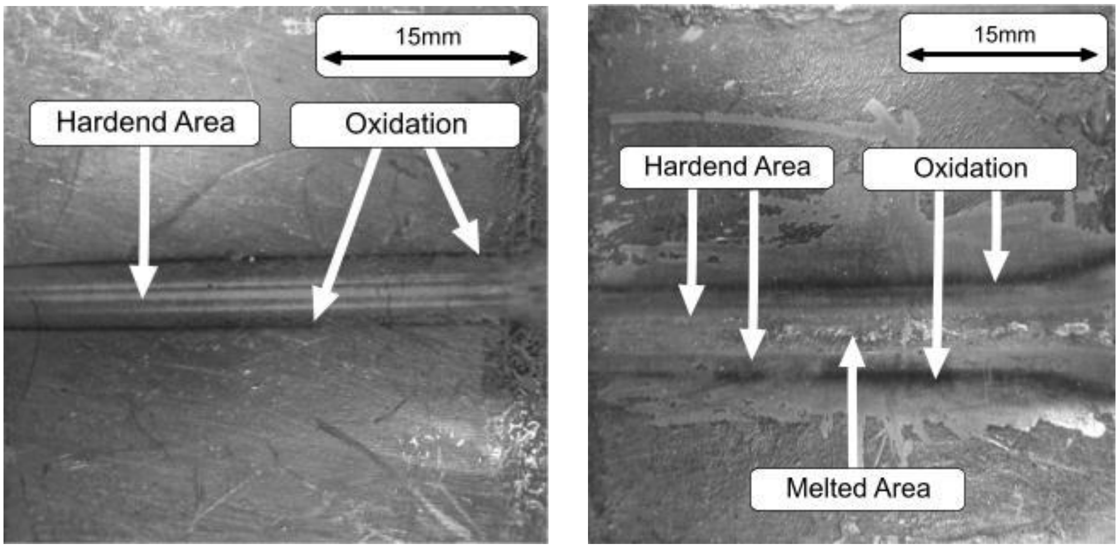

Figure 3. Example Laser Processed Specimen Before Testing a) hardened b) melted

3.2.1. Twin Valve Wear Testing

Samples were discs 60mm diameter, 9.5mm deep, made to fit onto the twin valve rig and incorporating the valve seat profile. Discs representing both typical inlet and exhaust geometries, with primary angles of 30° and 45° respectively, were made and each type had a nominal seating width of 2mm. Similar discs were made with cut-outs to accept actual valve seat inserts, again both typical inlet and exhaust. Examples of the specimens can be seen in Figure 4.

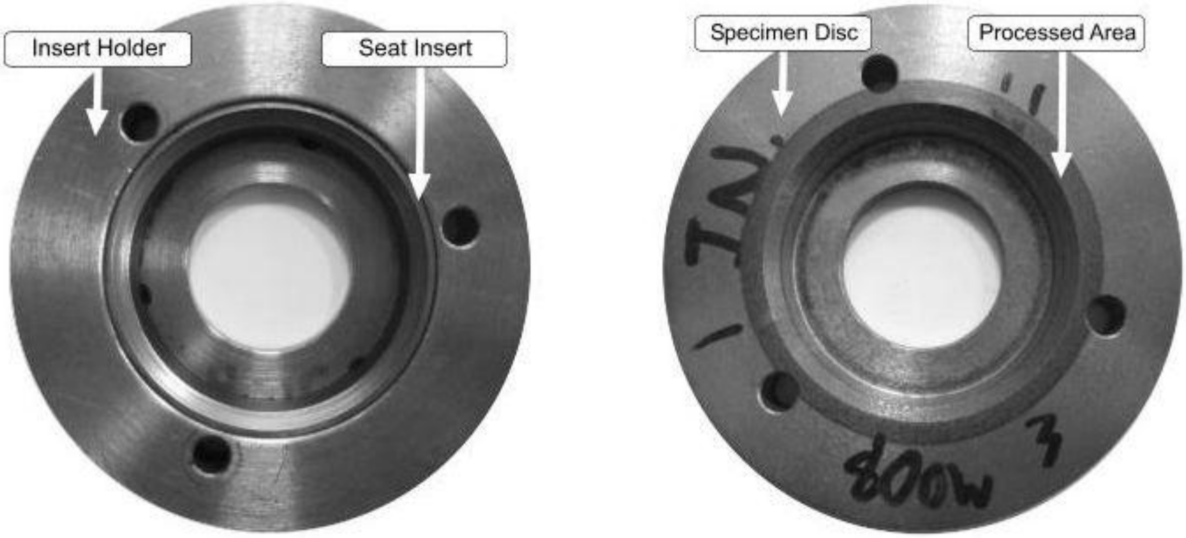

Figure 4. Sample for level 2 test with a) VSI b) inlet valve seat profile and laser treatment

The discs were treated on the valve seat face with a 6mm diameter spot from a diode laser at 480 mm min-1 with the laser power controlled by an optical pyrometer. Temperatures were chosen to be similar to the impact testing to give two depths of transformation hardening and one with melt and were 1000°C, 1200°C and 1300°C. It should be noted that due to the angles and the type of laser that was used for these specimens the graphite spray was not required and the absolute laser parameters are different to achieve similar material transformation to that for the impact wear tests. Potential manufacturing limitations, in terms of available processing time, were also taken into consideration. Table 3 shows the measured hardness and case depth of the specimens after processing.

Table 3. Twin Valve Specimen Properties

Specimen Set	**Temperature (°C)**	**Power (W)**	**Energy Density (J/mms^2)**	**Hardened layer**		**Melted Layer**	
				Depth (mm)	Hardness (HV)	Depth (mm)	Hardness (HV)
Set 1	1300	600	2.7	0.50	600-650	0.16	850
Set 2	1200	520	2.3	0.19	600-650	N/A	
Set 3	1000	450	2.0	0.12	600-650	N/A	

3.3. Test Procedures

3.3.1. Impact Wear Testing

Each specimen was tested at 10 impacts per second, with a striker closing velocity of 0.3m/s and an impact energy of 0.7J. Each of the three different test lengths was conducted with a new specimen and new striker and was repeated. The specimens and strikers were cleaned in ethanol prior to testing. The selection of these test parameters, in combination with the base test rig design, was designed to generate similar operating conditions to those in automotive valve train systems. Regardless of the actual thickness of the specimen after preparation, the surface of the specimen upon which the striker impacts was always in the same position in space.

3.3.2. Twin Valve Wear Testing

Each pair of specimens, one inlet and one exhaust, were tested simultaneously. The specimens were initially run for 18 hours and were then measured to check both alignment and contact were correct. They were then run up to a total of 100 hours and measured again. Due to time and cost restraints, an extensive program of repeats was not possible, however previous benchmarking work on the rig has shown good repeatability.

3.4. Wear Measurement and Assessment

For both types of testing the worn specimens were examined with a microscope and measured with a profilometer. The specimens were photographed and the wear scar geometries recorded after each test. The total wear was assessed by geometry change due to the very small fraction of the overall specimen mass being removed. Geometry change is also preferred as mass can be ‘moved’ via plastic deformation to a position where it can bear little or no load, a phenomenon that is undetected by mass difference techniques. The form and nature of any visible wear debris was also recorded along with any notable features. Selected specimens where sectioned and photographed to investigate subsurface deformations and features.

4. Results

4.1. Impact Wear Testing

The control specimens were measured first to provide a reference point for the other specimen sets. After 72000 impacts the average wear scar depth was 80µm with a average wear volume of 0.18mm^3.

4.1.1. Specimen Set A

The specimens that were treated at the slowest speed show the least wear of all the specimens. Figure 5 shows that there is some damage to the melted layer on the surface and that there is little subsurface deformation of either the hardened layer or the substrate. However, there is cracking due to the high solidification rate, which is not acceptable in a production component. The laser hardening process for this would need to be optimised to avoid cracks being formed in a production cylinder head. After 72000 impacts at 10Hz, or two hours of testing, the typical wear scar depth is around 40µm, as can be seen in Figure 6, with a total wear volume of 0.08mm^3.

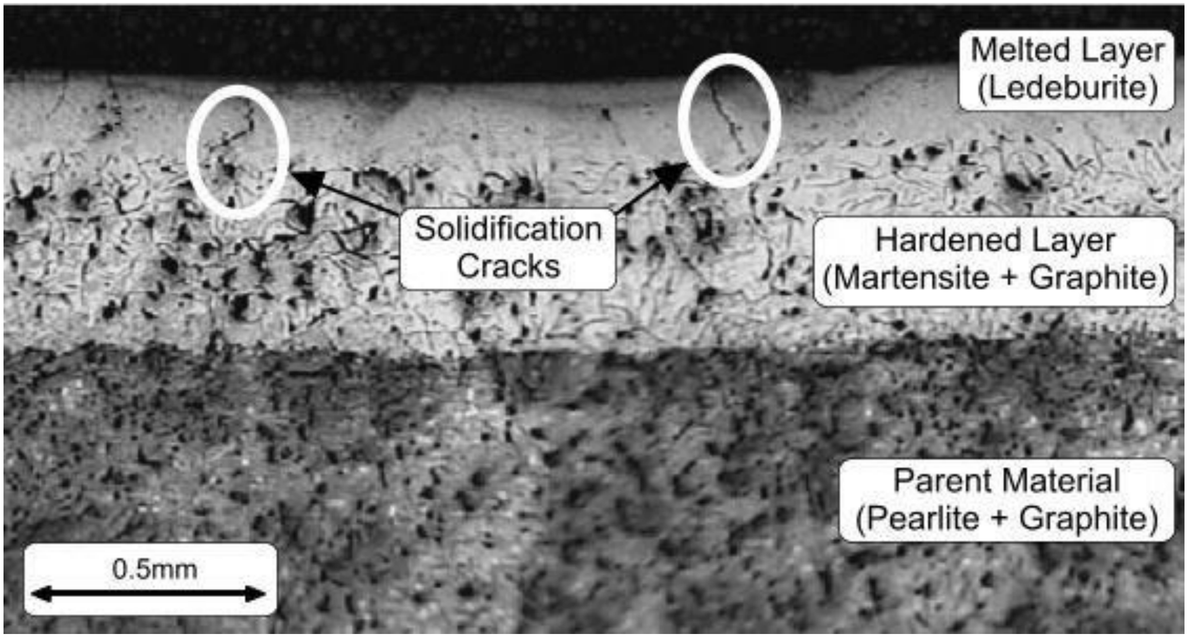

Figure 5. Section of wear scar, laser treated at 2mm/s and after 72000 impacts

mm