Hardened parts produced by Hard turning & Ball burnishing operations

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Abstract - ***T****he quality of work material's surfaces after undergone various manufacturing processes is very important in determining the functional performance of a component throughout the services. Application of coolant and lubricant in manufacturing operations such as turning, milling, grinding, rolling, etc. has been proven to improve the surface integrity of the work materials. In this paper, the application of cryogenic coolant in hard turning operations, and effect of Ball Burnishing operations was investigated in terms of its effects on surface integrity of the work materials which includes surface finish, micro structural changes, refinement of grain size, formation of white layer, residual stresses of internal subsurface layer, and surface hardness. Cryogenic application reduce the value of surface finish, but it allow for more comprehensive martensitic transformation, reduce the grain size, prevent the formation of white layer at the subsurface, reduce the tensile residual stresses and increase compressive stressed area, and finally increase the hardness of the work material. Burnishing is a cold working process in which plastic deformation occurs by applying a pressure through a ball or roller on metallic surfaces. It is a finishing and strengthening process. Improvements in surface finish, surface hardness, wear resistance, fatigue resistance, yield and tensile strength and corrosion resistance can be achieved by the application of this process. In this paper, sequential process of hard turning with and without cryogenic precooling of the work piece and ball burnishing operation is carried out. The main hypothesis tested in concerns with the fact that cryogenic pre-cooling slightly deteriorates surface finish but at the same time it enhance mechanical and service properties of the subsurface layer. 2D and 3D surface roughness, micro hardness of surface were studied.*

***Key Words*: Hard turning, Successful Hard Turning, Cryogenic machining, Burnishing, Surface & subsurface characterizations** etc.

1. INTRODUCTION

Hard turning is an important process because all manufacturers are continually seeking ways to manufacture their parts with lower cost, higher quality, rapid setups, lower investment, and smaller tooling inventory while eliminating non-value added activities[1]. The migration of processing from grinders to lathes can satisfy each and every one of these goals. The surface property of work material which undergone after various manufacturing process has a great importance in determine the functional performance of a component throughout the service. The application of coolant and lubrication during the machining operations such as turning, milling, grinding etc. helps to improve the surface integrity of the work materials [2] . In this paper, the application of cryogenic coolant in hard turning operations, and effect of Ball Burnishing operations were investigated in terms of its effects on surface integrity of the work materials which includes surface finish, micro structural changes, refinement of grain size, formation of white layer, residual stresses of internal subsurface layer, and surface hardness[3].

Cryogenic application is able to reduce the value of surface roughness, allow for more comprehensive martensitic transformation, reduce the grain size, prevent the formation of white layer at the subsurface, reduce the tensile residual stresses and increase compressive stresses area, and finally increase the hardness of the work material[6]. In conclusion, cryogenic application in a lot of manufacturing processes has been determined to be able to enhance and improve the quality of the work piece surface, consequently, boost the functional performance of the components.

Burnishing is a cold working process in which plastic deformation occurs by applying a pressure through a ball or roller on metallic surfaces[4]. It is a finishing and strengthening process. Improvements in surface finish, surface hardness, wear resistance, fatigue resistance, yield and tensile strength and corrosion resistance can be achieved by the application of this process.

Functional performance of a work material such as fatigue strength, corrosion rate, fracture toughness, and tribological behavior (such as friction, wear and lubrication, and accuracy of dimensions) are highly dependent on the surface properties. The integrity of the external surface topography (surface finish), microstructure, mechanical properties and residual stresses of internal subsurface layers are among the properties of a machined surface that affecting the functional performance. Therefore, surface integrity has been a subject of interest to many researchers in order to enhance the functional performance of work.

Many techniques have been investigated for the purpose of improving the quality of surface integrity in machining. Gentle machining is claimed to be able to enhance the surface integrity of machined surface compared to conventional machining. Gentle machining can be defined as machining in a "low stress conditions" which will result in little heat generated at the cutting zone[3]. In order to achieve the low stress conditions in machining, many attempts have been explored, and application of cutting fluid is among one of them. Cutting fluid is applied during machining for the function of cooling and lubrication. Coolant is important to cool the heat generation zone in machining process; meanwhile lubricant is used to minimize the friction between the tool, chip and work piece interface. Methods of cutting fluid application include flood machining, near-dry machining and also cryogenic machining. Cryogenic acts as coolant to reduce the temperature generated in machining process. Cryogenic coolant uses liquid gaseous such as liquid nitrogen (LN2) or liquid carbon dioxide (CO2) to reduce the temperature at the cutting zone[6]. materials.

Cryogenic machining is more advantageous compared to the usage of conventional cutting fluid in terms of eco friendly in such a way that the liquid gas used will evaporate into the air and become part of the atmosphere[7]. The evaporation of the gaseous also eliminate the cost of cutting fluid disposal. A lot of researches have been conducted to study the benefits of cryogenic application in manufacturing processes. Cryogenic application is claimed to improve process sustainability, increase material removal rate (MRR), enhance the tool life, improve product quality of machined parts and enhance surface integrity[12].

1 LITERATURE REVIEW

1.1 Hard Turning

Hard turning is defined as the process of single point cutting in work pieces that have hardness values more than 45 HRC but more specifically the ranges are 58-68 HRC range[8]. The most commonly used cutting tools are Cubic Boron Nitride (CBN), Ceramic and sometimes Cementite. Selection of tool choice should be matched with the application, desired production rates, surface finish, quality and operating cost goals. The most prominent selection of cutting tool is CBN for the more demanding applications of size , finishing and it can also used for those components which had been transitioned from grinding. In 2001 the sales of CBN tools exceeded $250 million, providing an idea of broad use of this technology. The CBN cutting tools are available in several grades and selection should be properly match the requirements. As an example, a low content CBN inserted tool will not perform well in an interrupted cutting application because it lacks the necessary toughness[8]. Generally, high content CBN inserted tool have higher toughness whereas low content inserted tool provide longer tool life in straight turning applications.

In the beginning of nineties hard turning was really started to develop. The reason for this was the availability of new tool materials and the capability of designing of turning machine (lathe) that was rigid, stable and accurate, which were enough to successfully finish hard turning operation. These developments which leads to made that the hard turning is a possible alternative to grinding as an accurate finishing operation[5]. Hard turning can effectively replace the pre-grind roughing operations. If one lists the current applications of hard turning it would certainly be a voluminous document. In olden days the following few industries were the commonly used hard turning technology Automotive, bearing, marine, punch and die, mold, hydraulics and pneumatics, machine tool and aerospace. But now a days many industries segments are adopting hard turning because it is an unavoidable machining operation.

The typical materials, which are routinely hard turned, include those of the following broad category descriptions:

- Steel alloys
- Bearing steels
- Hot and cold work tool steels
- High speed steels
- Die Steels
- Case hardened steels

Fig -1: Hard turning operation

In the above figure 1 HRC 62 hard part is being machined without coolant, and it is clear that the chip temperature is extremely high, and in fact the cutting zone in dry operations, is normally in the range of 925 degrees Celsius. The localized heating that occurs at the tool tip tends to easier in the cutting action, since the heat generated at the tool tip begins to anneal and soften the material just ahead of the tool, making it easier to shear[8]. A measurement of the hardness of the cut chips will frequently show values, which are below one-half of the hardness of the base material. This will also explain improvement in tool life in some applications because the material has been annealed to lower hardness levels.Hard turned surfaces frequently produced white layer,which is due to either severe plastic deformation that causes rapid grain refinement or phase transformations as a result of rapid heating and quenching.

1.1.1 Successful Hard Turning

Successful hard turning is dependent upon the entire machining system and not just certain discrete elements. As a way of summary the following items are related to successful hard turning applications.

- A machine with a high dynamic stiffness.
- Efficient work holding devices.
- A correctly chosen CBN grade or other tooling material type.
- High quality cutting edges.
- Rigid tool mounts.
- Appropriate machining parameters.
- Work piece rigidity.
- Chip management and cooling systems

Good vibration damping characteristics.

1.2 Cryogenic Machining

The cryogenic machining is a process of jetting a small quantity of liquid nitrogen in to the rake phase of cutting tool. During the cutting process liquid nitrogen LN_2 can be stored with a bulk tank outside the building or it can be stored very close to machine by a pressurized cylinder, from there it can be transported through a vacuum lines [7]. There is a control box integrated with the machine controller which provides signal fir liquid nitrogen LN_2 to flow according to the demand through flexible lines in to the specifically designed nozzles. The nozzles are fixed in to the clamp or which are mounted close to the tool. The nozzle discharges a stable precise LN_2 jet towards the chip tool interface.

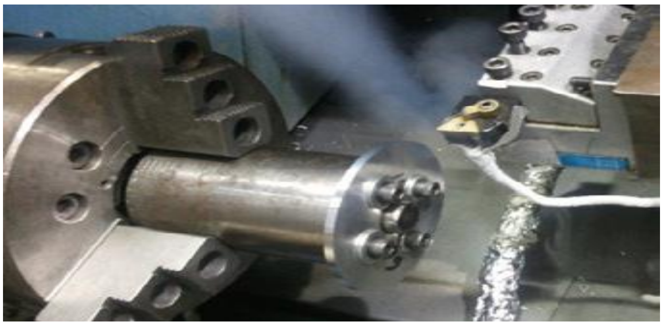

Fig - 2: Experimental set up for cutting operation with cryogenic coolant system

Fig - 3: Nozzle position for cryogenic coolant delivery

The Liquid Nitrogen is used as a coolant in cryogenic machining. The liquid nitrogen using in machining process, it evaporated suddenly and return back to atmosphere, when it is delivered to cutting zone. During evaporation takes place there is no residue to contaminate the parts, chips, machine tool or operator [9].

1.2.1 Benefits of cryogenic machining

- The friction coefficient is reduced on tool-chip interface.
- Liquid Nitrogen is applied in cutting zone which is superior than other conventional coolants in lowering the cutting temperature.
- Lower in abrasion and chemical wear which increases in tool life.
- Increased material removal rate with no increase in tool-wear and also cutting tool change over cost, which results in higher productivity.
- Improved machined part surface quality with the absence of mechanical and chemical degradation of the machined surface.
- Liquid nitrogen can store and transport with less cost and very easy.

1.3 Burnishing

Burnishing is the plastic deformation of a surface due to sliding contact with another object. Visually, burnishing smears the texture of a rough surface and makes it shinier[4]. Burnishing may occur on any sliding surface if the contact stress locally exceeds the yield strength of the material. Burnishing processes are used in manufacturing to improve the size, shape, surface finish, or surface hardness of a work piece. It is essentially for forming operation that occurs on a small scale. The benefits of burnishing often include: Combats fatigue failure, prevents corrosion and stress concentration, textures surfaces to eliminate visual defects, closes porosity, creates surface compressive residual stress[11].

There are several forms of burnishing processes; the most common are roller burnishing and ball burnishing. In both cases, a burnishing tool runs against the work piece and plastically deforms its surface[4]. In case of ball burnishing, it rubs, and at in case of roller burnishing it generally rotates and rolls. The work piece may be at ambient temperature, or heated to reduce the forces and wear on the tool. The tool is usually hardened and coated with special materials to increase its life.

Ball burnishing, can be used as a replacement for other bore finishing operations such as grinding, honing, or polishing [11]. A burnishing tool consists of one or more over-sized balls that are pushed through a hole. Ball burnishing is also used as a deburring operation. It is especially useful for removing the burr in the middle of a through hole that was drilled from both sides.

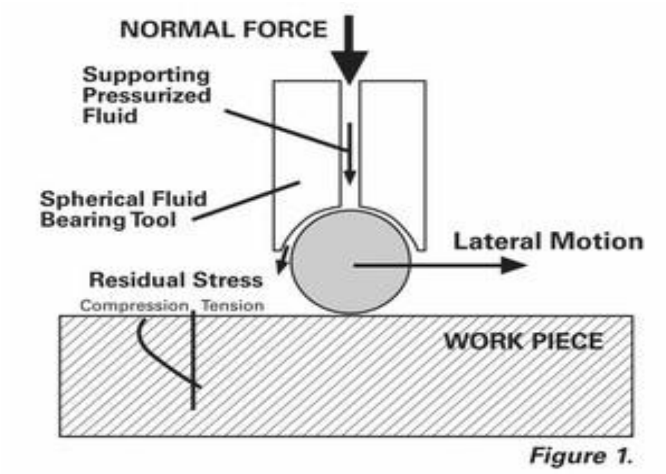

Fig – 4: Ball burnishing process

2 EXPERIMENTAL DETAILS

The experiment setup consist of Work piece material, tooling and machining conditions. Hard machining trials were performed on the specimen made of 41Cr4 steel with Rockwell's hardness of 57±1 HRC. Here very low content (about 60%) CBN tool were used. The work piece is made in to two state 1) Dry state 2) Cryogenic Pre cooled state

In case of cryogenic pre-cooled state, the work piece is kept into a specially cooled chamber with liquid nitrogen (LN_2).The cryogenic treatment carried out on work piece about 3-4minutes.The machining of cryogenic treated work piece (frozen material) is carried out after 30 s. This 30 s is taken for transferring the work piece from cooling chamber to the machine tool.

Hard turning conditions were as follows:

- cutting speed of 150 m/min,
- variable feed rate of 0.075 (HT1/CHT1), 0.1 (HT2/CHT2) and 0.125 (HT3/CHT3) mm/rev,
- depth of cut of 0.15mm/rev.

Both hard turning processes were performed on a conventional lathe and a CNC turning center.

Table - 1: Specification of dry and cryogenic hard turning operations

Dry hard turning		Cryogenic hard turning	
Feed rate mm/rev	code	Feed rate mm/rev	code
0.075	HT1	0.075	CHT1
0.10	HT2	0.10	CHT2
0.125	HT3	0.125	CHT3

In case roller burnishing was carried out by static ball. The burnishing tool (ball) consist of 12mm diameter made by Ceramic (Si_3N_4). The desired load is generated by spring based pressure control system.

Burnishing conditions were as follows: burnishing speed of 25 m/min, burnishing feed *fb* of 0.05 (HT1/CHT1 + B1), 0.075 (HT2/CHT2 + B2) and 0.1 (HT3/CHT3 + B3) mm/rev, which was always lower than turning feed *ft* and the tool correction of 0.25 mm in the CNC control system.

Multi pass Burnishing consisting of 4 passes (HT2 + B2 M/CHT2 + B2 M),and one pass (HT1 + B1/CHT1 + B1, HT2 + B2/CHT2 + B2,HT3 + B3/CHT3 + B3) burnishing operations after dry and cryogenic turning operations were performed at constant load of about 600N. Both hard turning and burnishing operations were performed on a CNC turning center, Okuma Genos L200E-M[13].

Table - 2: Specifications of burnishing operations

Feed rate *fb* (mm/rev)	Code
0.05	B1
0.075	B2,B2M
0.10	B3

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2.1 Surface and subsurface characterizations

A Profilometer with a diamond stylus at a radius of 2μm were used for recording surface profiles/topographies, and also estimating roughness parameter of 2D and 3D on the scanned areas of work piece. LECO hardness testers with a Berkovish identer at a load of 50G were used for measuring the micro hardness of machined and polished samples across the subsurface. The variation of hardness about 100μm in the subsurface layer is determined. There is a chance to interference of indentations. To avoid this interference of indentations, the measurements are taken on oblique sections inclined at an angle of 3^0 to the outer surface. The strain-hardening rates related to the maximum values of micro hardness in the subsurface layer were computed.

A scanning microscope, model HITACHIS-3400N which is equipped with X-ray diffraction head EDS, model THEMONORAN System Six were used for examining the changes of microstructure and texture by burnishing process . The images obtained from microscope such as (BSE, SEM) were recorded. The sections, which are mechanically and chemically polished were, performed in this analysis.

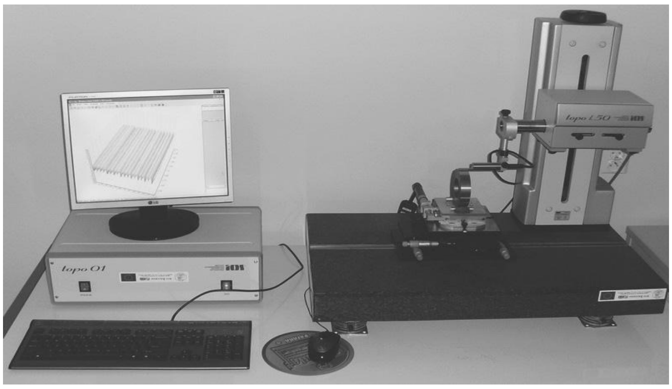

Fig - 5: 3D profilometer, model TOPO 01P

3 RESULTS & DISCUSSION

3.1 Geometrical features of turned and burnished surfaces

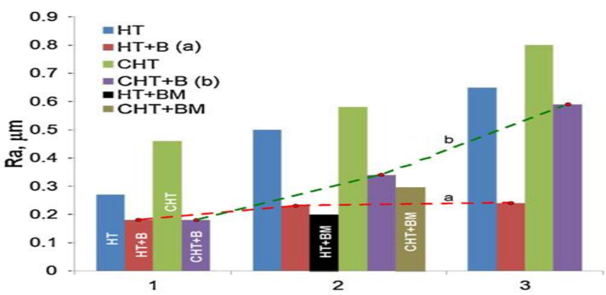

Fig - 6: Comparison of Ra parameter for hard turned and burnished surfaces

Burnishing process leads to change the initially turned surfaces in their shape and geometrical features as shown in Fig.6 .The Ra parameter is represented in vertical distance, which is reduced by burnishing process with different feed as shown in Fig.6.The Ra parameter is reduced by burnishing process but this effect is more noticeable in dry HT. The minimum value of Ra = 0.18 μm was obtained for variant 1 (HT/CHT + B1). From Fig.6 we can understand that, in case of cryogenic HT process produces a higher peak value profile. But burnishing process is able to change this turned profiles effectively (by reducing Ra parameter) at smaller feeds[13]. The effect of burnishing process leads to increased hardness, strength and also coarser microstructure of the freezing work piece. Cryogenically cooled harder material are brittle and chip removal depends upon the brittle fracture.

Cryogenic cooling of the work piece leads to sudden increase in strength and hardness of work piece, which result higher cutting resistance[7]. For an example, the hardness of AISI E52100 bearing steel increases two times when temperature decreases from about 100◦ C to about −200◦ C. As a result, when hardness of material increases, the surface finish after machining is very poor than the surface finish of lower hardness material after machining.

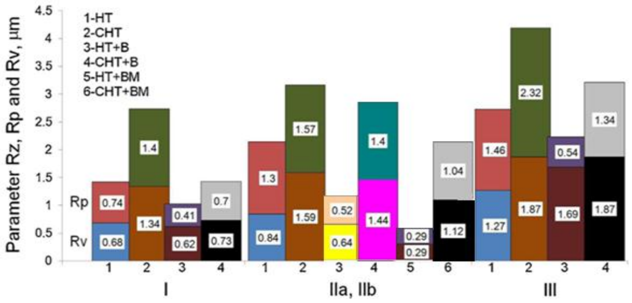

Fig – 7: Comparison of Rz roughness parameters for hard turned and ball burnished surfaces

The second observation is that the component of Rz is Rp and Rv. The Rz is depends on the initial profile shape, as shown in Fig 7. Depending on the turning feed, the peak height Rp reduced to 45-75%, but the valley depth Rv is reduced on average, of 10%.

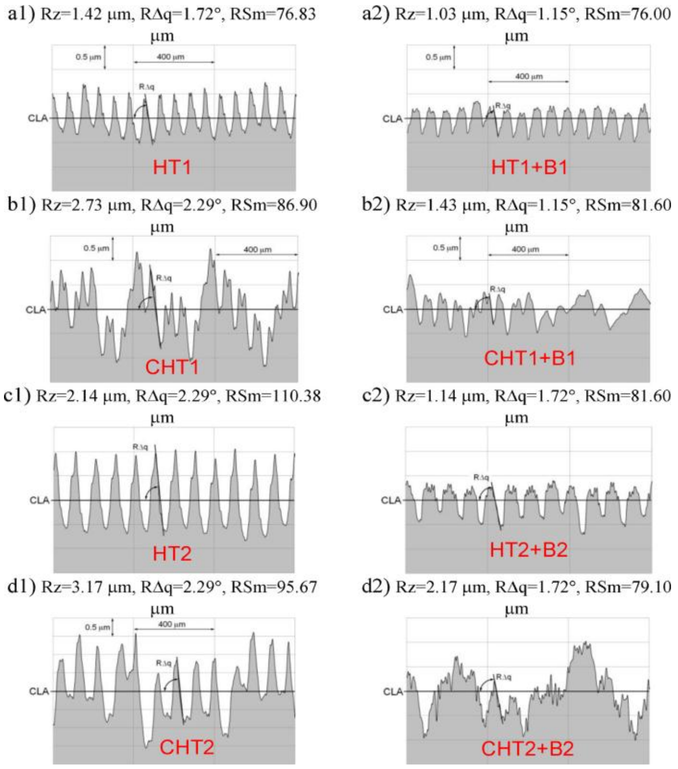

Fig – 8: Modification of surface profiles by Burnishing

Fig.8 indicates that dry hard turning (HT1) produces a surface profile having an interval of regular tool nose. The feed value is equal to Rsm Parameters. The slope R∆q, generally not greater than 2^0. In the case of (HT1+B1/CHT1 + B1), burnishing produces a profile which removes the sharp peaks with in Rp height. The Rsm parameter does change practically. In the case of (HT2 + B2) and (HT3 + B3) higher irregularities are partially break into smaller pieces and severely deformed, and which is flattened finally. The new modified profiles were produced which having lower spacings between peaks[13]. For example, RSm decreases almost three times (124.50 μm vs. 44.94 μm) for multi-pass burnishing(HT2 + B2 M).

3.2 Micro hardness and strain–hardening effects

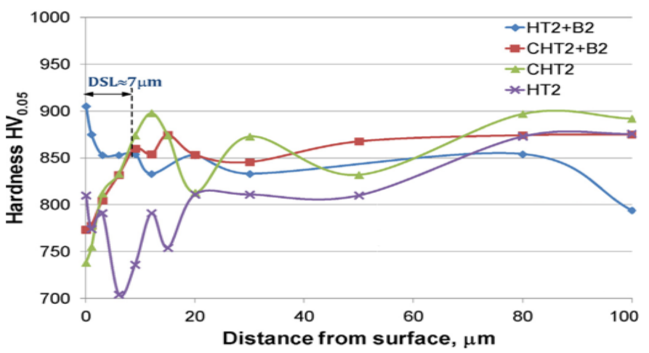

Fig – 9; Micro hardness and strain–hardening effects

Distribution of micro hardness in the subsurface layer at a distance of 100 μm from the surface is measured using LECO hardness tester MHT Series 200 with a Berkovich indenter at a load of 50G. In case of dry hard turning and after burnishing made that maximum micro hardness is localized close to the surface. But in case of cryogenic cooling the maximum hardness is to shift to the point beneath the surface (12–15 μm). The maximum micro hardness in case of dry hard turning is measured directly underneath the generated surface was about 830 MPa. In case of burnishing (HT2+B2) this value is 905Mpa[13].In case of cryogenic hard turning process (CHT2) process white layer is not produced. The result of micro hardness in the zone adjacent to the surface is about 740 MPa. Which can be increased slightly by burnishing to 775 MPa.

3.2 Micro structural alterations into the surface layer

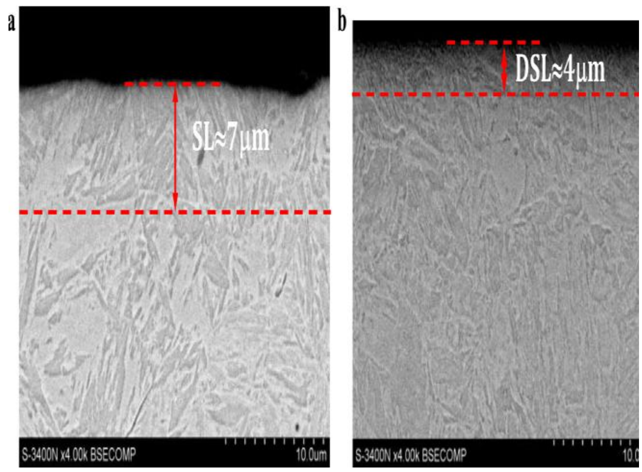

Fig - 10: Micro structure of surface layer after HT2 and HT2+B

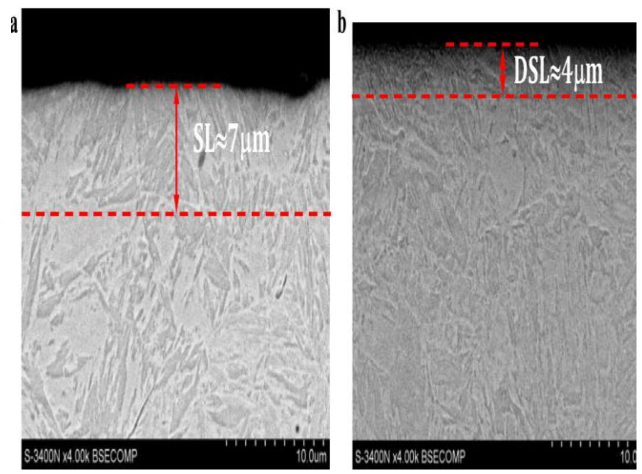

Fig - 11: Micro structure of surface layer after CHT2 and CHT2+B

The SEM/BSE techniques were used for Micro structural analysis and EDS technique is used for phase content measurements. The EDS technique also helps to identify the structural effect of burnishing process and also it helps to determine the chemical composition of the surface layer. The above figures shows BSE micro photographs of surface layer (SL) produced by dry hard turning and cryogenic hard turning. It also indicates the modifications induced by sequential burnishing. In the case of cryogenic machining surface of the work piece will be cold during machining and It is shielded by a frozen skin .The IR camera is used for determining the cutting temperature.. It indicates that 600K and 800 K (correspondingly about 300–500°C) for cryogenic machining and in case of dry hard turning with cutting speed of 150m/min was about 800°C[13]. From the result of IR camera the micro structure does not change after hard machining of cryogenically pre-cooled work piece due to low cutting temperature. But the of SEM analyses performed, it indicates that after cryogenic treatment the content of retained austenite decreases and surface layer formation is very low (less intensive). The BSE images indicate that, the work piece, which pre cooled by liquid nitrogen will not produced white layer (WL). But in case dry hard turning (dry HT) white layer is formed and it penetrate about 3 µm below the machined surface. At the same time, while machining the work piece which is pre cooled by liquid nitrogen produced submicron dispersive carbides. The white layer (WL) is restored in the form of a nano crystalline homogeneous layer after burnishing (HT2 + B2).In this case indicate that after burnishing severely deformed surface layer (DSL) is formed just below the white layer about 7µm thickness. This image also shows martensite structure with the grain boundaries of retained austenite.

4 CONCLUSION

From the above study we can conclude that,

- In hard turning, the burnishing process is able to modify surface and subsurface layer.
- Cryogenic pre cooling in materials (work piece) can be used as a additional control on the effect of burnishing.
- Burnished surfaces which are exactly flattened have a better bearing properties.
- The best response results were obtained at the lowest value of burnishing feed. Feed rate is also the most significant factor in the roller burnishing process.
- Apart from high hardness of the steel machined, the surface layer is additionally strain-hardened by burnishing. For extremely hard steel, the strain–hardening ratio is in the range of 5–10% depending on the initial state of work piece (with or without cryogenic pre-cooling).
- White layer formation can be controlled by cryogenic pre cooling of work piece.
- White layer (WL) is not formed in hard turning (CHT+B) of cryogenic pre cooled workpiece and the thickness of sub layer is reducd.
- The fine martensite formation by a specific deformation in ball burnishing operation is the basic mechanism of increasing the hardness of surface layer.

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