

Advances in the surface defect machining (SDM) of hard steels

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Abstract:

This paper reports the realisation of precision surface finish (Ra 30 nm) on AISI 4340 steel using a conventional turret lathe by adapting and incorporating a surface defect machining (SDM) method [Wear, **302**, 2013 (1124-1135)]. Conventional ways of machining materials are limited by the use of a critical feed rate, experimentally determined as 0.02 mm/rev, beyond which no appreciable improvement in the machined quality of the surface is obtained. However, in this research, the novel application of an SDM method was used to overcome this minimum feed rate limitation ultimately reducing it to 0.005 mm/rev and attaining an average machined surface roughness of 30 nm. From an application point of view, such a smooth finish is well within the values recommended in the ASTM standards for total knee joint prosthesis. Further analysis was done using SEM imaging, white light interferometry and numerical simulations to verify that adapting SDM method provides improved surface integrity by reducing the extent of side flow, microchips and weldments during the hard turning process.

Keywords: Surface defect machining (SDM); hard turning; surface roughness

Abbreviations:

<i>AISI</i>	<i>American Iron and Steel Institute</i>
<i>CBN</i>	<i>Cubic boron nitride</i>
<i>CNC</i>	<i>Computer numerically controlled</i>

<i>FEA</i>	<i>Finite element analysis</i>
<i>HT</i>	<i>Hard turning</i>
<i>HRC</i>	<i>Rockwell C scale hardness</i>
<i>MD</i>	<i>Molecular dynamics</i>
<i>SDM</i>	<i>Surface defect machining</i>

1. Introduction

The hard turning (HT) process has now become a viable method for machining automotive components, exhibiting high hardness well above 45 HRC. The extant literature reports various concerns that restrict its exploitation, the foremost of which is the unexpected failure of the machined component while in use [1-4]. Such failure is believed to be due to the formation of the white layer both on and underneath the finished machined surface [2, 5-8] caused by the tensile residual stresses on the machined surface [9-14]. This imposes serious risks regarding the potential fatigue life of components [15-17]. To avoid this, it is important that the machining process should induce minimum residual stresses, minimise the average value of the machined surface roughness and ensure that the quality of the machined surface is such that it is free from defects such as cracks, cavities etc. The degradation of the finished machined surface is often referred to as “surface deterioration” which is predominantly caused by excessive plastic side flow, the build-up of the workpiece material and microchips formed during the course of the HT process. However, there are several other forms of surface deterioration mechanisms which appear in the form of cracks, grooves, cavities and the formation of hard dynamic particles due to the high machining temperature.

Much of the literature questions the reliability of HT and prefers grinding as a potential solution [18]. As a consequence of this concern, in this work, a surface defect machining (SDM) HT method is proposed as a solution to address this problem and to demonstrate that purpose designed and manufactured surface defects can be produced in a controlled manner on the workpiece,

demonstrating HT as a viable solution which can improve surface finish and surface integrity. SDM is a relatively new approach which was primarily developed to machine hard ferrous alloys [19] at macroscale but has been shown theoretically to be applicable down to the nanoscale for machining brittle materials such as silicon carbide [20]. It has been demonstrated that SDM harnesses the combined advantages of both porosity machining [21] and pulse laser pre-treatment [22] as shown in Figure 1 by machining a workpiece by initially generating surface defects at depths less than the uncut chip thickness through either mechanical means and/or thermal means followed by a routine conventional machining operation.

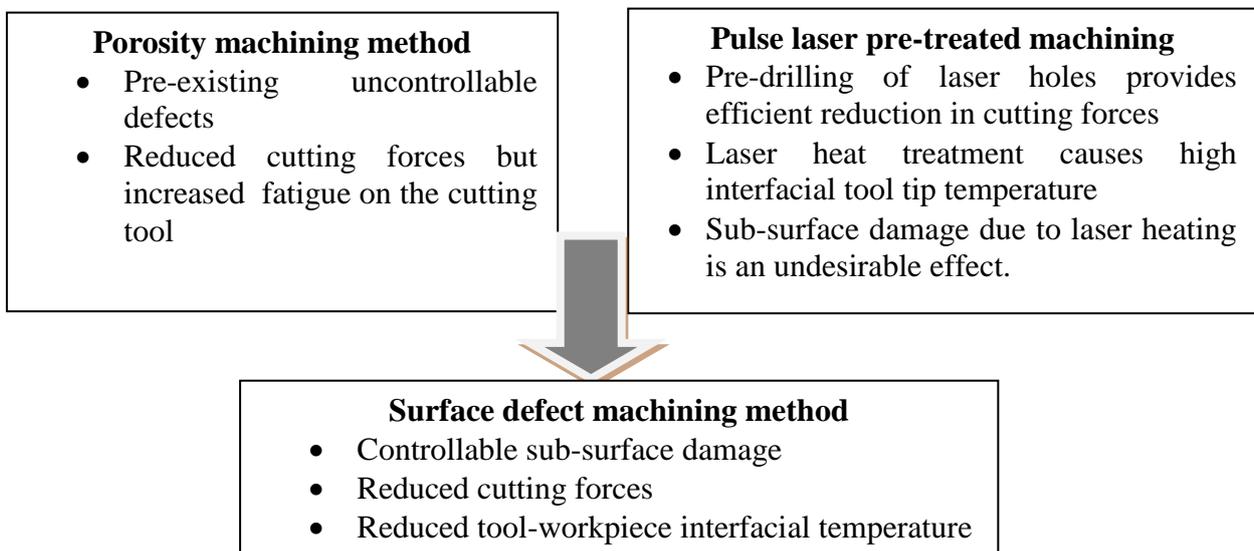


Figure 1: Development of the surface defect machining method [23]

State-of-the-art modelling and simulation methods [23] have been used to discover a number of promising features of the SDM approach including lower machining forces, reductions in overall temperature in the cutting zone, reduced machining stresses and increased chip flow velocity. An interesting observation during these studies was that the SDM mechanism alters the chip morphology from jagged to discontinuous. This ties in with the fact that SDM enables ease of deformation by shearing the material at reduced input energy [23]. Also, due to the large proportion of stress concentration in the cutting zone - rather than the sub-surface – it enables a reduction in the associated residual stresses on the machined surface.

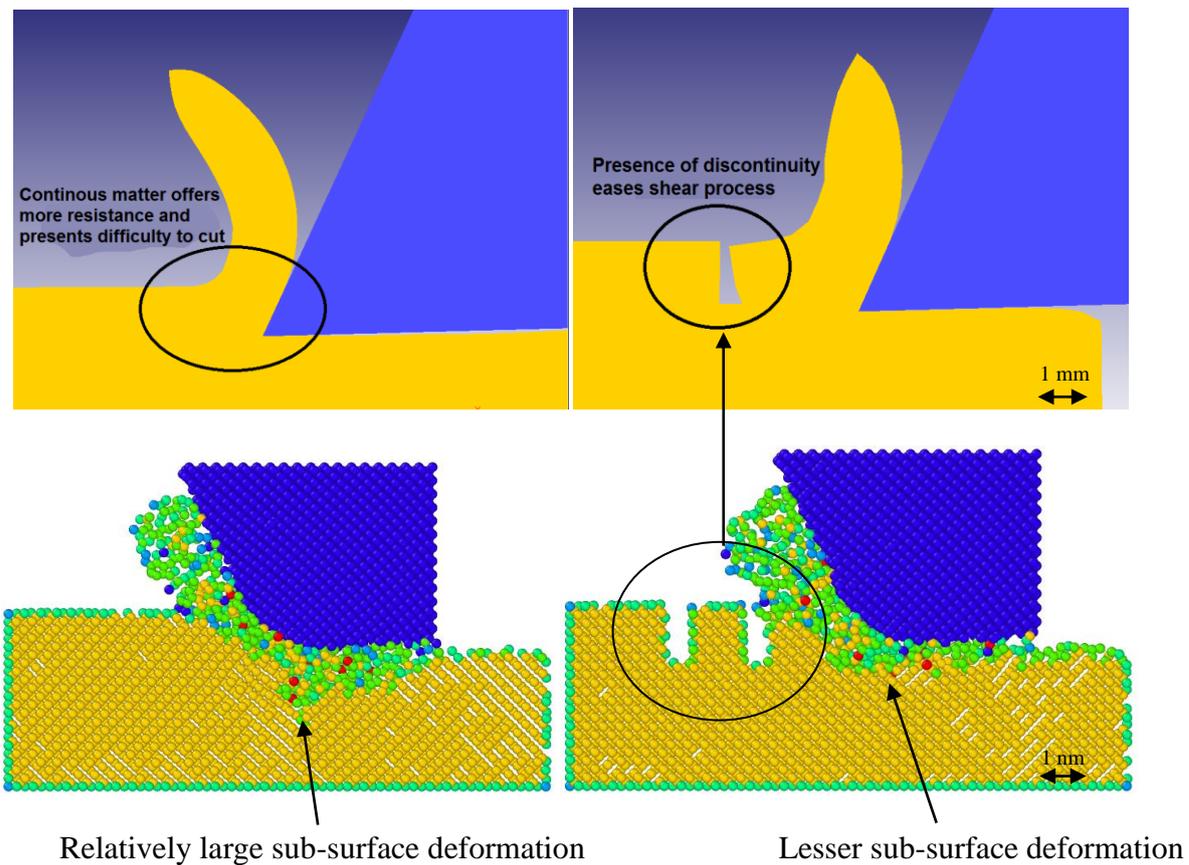


Figure 2: Schematic diagram indicating the differences between the mode of deformation during conventional machining and SDM observed through FEA simulation of hard steel and MD simulation of silicon carbide respectively.

The motivation for developing the SDM method originated from the hypothesis that changing the removal mechanism for cutting chips from continuous to discontinuous minimizes the problems caused by continuous cutting especially during HT. The cutting chips during HT can collide either with the machined surface or with the cutting tool which could damage the surface quality of the part being machined. Moreover, surface discontinuities break the energy barriers associated with the critical deformation load, i.e. the surface defects allow easy shearing of the material as shown schematically at two different scales in Figure 2. Therefore, SDM provides a product which has good surface integrity compared to that obtained using conventional hard turning. These advantages point to the fact that a component machined using the SDM method should exhibit improved quality of the machined surface; therefore, an experimental investigation to test this hypothesis was employed and is outlined in this paper.

2. A brief review of the hard turning studies concerning surface quality

In his seminal work, Bailey identified and characterized some of the surface defects on hard turned quenched and tempered AISI 4340 steel (56 HRC) [24]. He categorized those surface defects into coarse and fine scale defects as shown in Table 1. This study showed that the observed coarse scale defects are associated with continuous chip formation and appear in the form of weldment particles on the machined surface whereas fine-scale defects are associated with discontinuous chip formation and mostly appear in the form of cavities, surface tearing and microcracks on the surface [25].

Table 1: Qualitative characterization of various surface defects – adapted [24, 26]

Coarse-Scale Defects	Fine-Scale Defects
Side flow/pile-up	Micro-Cracking
Weldment particles (hard dynamic particles)	Surface tearing
Microchip debris	Cavities
Grooves	Plastic flow
Ridges	Deformation of the grains

Table 2: Review of the work on surface deterioration

Workpiece	Observations/ conclusions	Reference
Inconel 718	Observation of a wide range of surface damage (side flow, pile-up material, grooves and ridges and micro-cracking).	Zhou J., <i>et al.</i> , 2011 [26]
A15083-H116	Surface roughness model involving consideration of plastic side flow.	Liu K., <i>et al.</i> , 2006 [27]
AISI 4615	SEM examination revealed presence of surface damages due to formation of weldments.	Kishawy and Elbestawi, 1999 [28]
General category	Presents a phenomenological analysis of material side flow in hard turning.	El-Wardany and Elbestawi, 1998 [29]
Hardened steel (60 HRC)	Proposed material side flow dependent on the cutting conditions and tool geometry.	El-Wardany and Elbestawi, 1993 [30]
Annealed 18% nickel maraging steel (28 HRC)	Confirmed the presence of coarse and fine scale defects.	Bailey, J.A. 1977 [25]
Quenched and tempered AISI 4340 steel (56 HRC)	Comprehensive explanation of the effects of cutting speed, tool wear and land length on surface integrity.	Bailey, J.A 1976 [31]
AISI 4340 steel	Surface defects categorized into coarse and fine scale defects (Table 1).	Bailey, J.A. 1974, [24]
Plain carbon steel	Concluded that side flow and pile-up in metal cutting are responsible for poor surface roughness	Selvam, M. <i>et al.</i> , 1973 [32]

	quality.	
CK 45 steel (SAE 1045)	During finish turning, surface microchips are displaced in a direction opposite to the feed direction and eventually these form burrs	Pekelharing, A. <i>et al.</i> , 1971 [33]
General	Identified factors affecting surface roughness such as the formation of a pile-up, swelling of the work material, vibration and tool wear.	Sata T., 1966, [34]

Generally, fine scale defects do not contribute to surface roughness as much as the coarse scale defects; therefore, it was important to identify these kinds of defects. Selvam *et al.* [32] pointed that side flow and welded material are major factors responsible for increased machined surface roughness. In subsequent work [2], Bailey mentioned that the nature of the surface region is influenced primarily by the two important factors, namely: the high temperature generated during the course of machining and the friction at the interface between the workpiece and the cutting tool. A summary of similar related work with different outcomes is shown in Table 2 to highlight that much of the previous research work attempted to relate surface damage to key machining parameters such as depth of cut, cutting speed and feed rate as well as tool geometry such as the rake angle and tool nose radius [25, 27-29]. Indeed the state-of-the-art currently assumes that these parameters are the only variables that can be optimised in order to improve machining performance and, subsequently, the machined surface roughness. While this has been attempted in a number of studies by applying various optimization techniques it has only resulted in a limited level of success [35]; however, this paper improves on these methods by demonstrating that this can better be accomplished by adapting the SDM method to this problem domain. In order to visualize such a phenomenon carefully, it is essential to understand and categorize all the major types of surface defect so that they can be practically analysed and compared during machining trials combining SDM with conventional machining. Therefore, the following section classifies all such defects commonly observed during conventional HT finished machining.

2.1. Side flow and pile-up edges

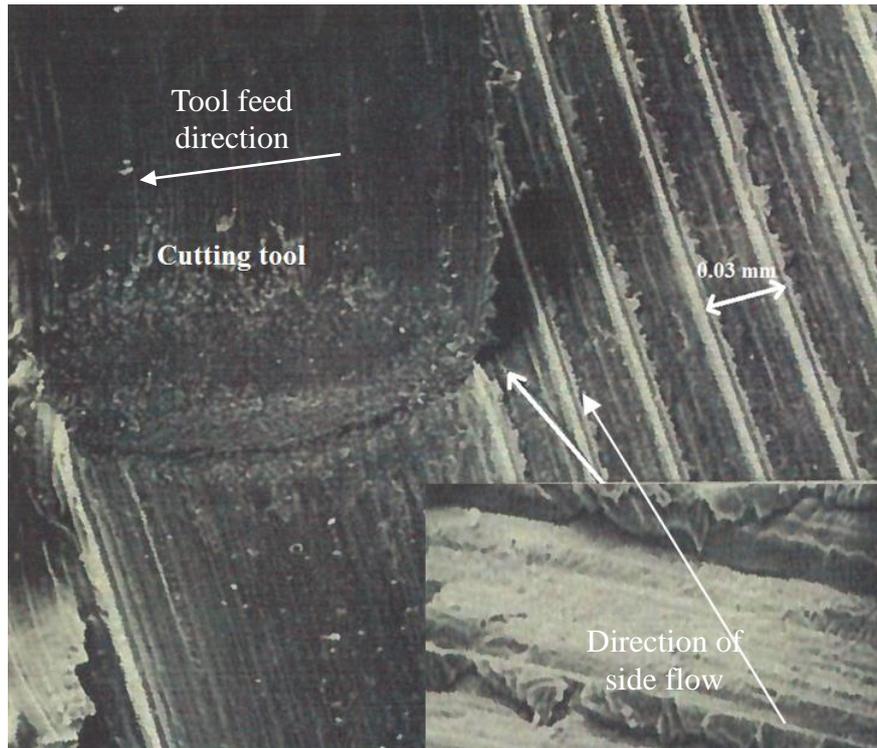


Figure 3: High speed camera image of the cutting zone showing a close up view of the machined surface – adapted [33].

In their pioneering work, Pekelharing and Gieszen [33] presented photographic evidence of the occurrence of the pile-up and side flow with the aid of a high speed imaging camera as shown in Figure 3. They demonstrated that the workpiece material displaced sideways by the cutting tool in any cutting operation is analogous to the observations found during a classical indentation process. As shown in Figure 3, the direction of the side flow on the machined surface appears to be opposite to the direction of the feed rate. This extra material is removed by the cutting tool during the course of machining, leading to abrasion, surface corrosion and micro-cracking [29]. Furthermore, the adhered material is hard, has a tendency to abrade and is therefore apt to wear the working surface to which it comes in contact with [28]. Liu *et al.* [27] and Sata *et al.* [36] have stated that, together, side flow and pile up are the most important types of surface deterioration and can influence surface roughness by up to 6 μm . Wardany *et al.* [29] indicated that side flow is heavily influenced by the cutting tool nose radius, feed motion and the progression of the tool wear resulting in an altered cutting tool profile. Other researchers [28, 36, 37] mentioned that cutting speed has a significant

influence on material side flow. Bresseler *et al.* [38] postulated that tool geometry is the most important factor while Shaw [37] indicated that plastic side flow is most significant at fine feed rates and could be partly responsible for the rise in surface roughness at considerably smaller feed rates.

2.2. *Weldment particles*

Weldments are small globular particles which are believed to form at high machining temperature that promote ideal conditions for welding in the finer and fractured built up edges of hard steel. The growth of weldment particles is strongly dependent on the extent and rate of the formation of built-up edges. Such particles could potentially be referred to as hard dynamic particles [39, 40] and are deemed to be harder than the pristine workpiece material. As has been recognized, dynamic hard particles (weldments) have the tendency to cause abrasive wear, thereby deteriorating the quality of the machined surface finish. During this abrasive action they may also travel along the cutting edge of the tool leaving a trajectory of their motions on the finished machined surface. This trajectory eventually appears as small grooves on the finished machine surface. When such a part is subjected to contact interactions, these weldment particles becomes a source of abrasion with the part with which they come into contact with.

2.3. *Microchip debris/grooves/ridges*

In an investigation on hardened AISI 4340 steel, an explanation on the formation of the microchip was offered [31]. It was highlighted that there could be an instance where the formation of secondary chips takes place which are referred to as microchips. These microchips are classified into three categories: (i) those which leave a groove behind them on the finished machined surface without making a physical separation from the bulk workpiece; (ii) those which leave their impressions on the surface and also separate from the workpiece in the form of small debris; and (iii) those formed as consequence of the formation of a Beilby material layer [41] due to the interaction between the cutting tool and the workpiece forming a microchip in categories (i) or (ii). These microchips exhibit characteristics to abrade and worsen the finished surface [38].

From this brief review, it appears that there are many factors which could jointly be responsible in influencing the machined surface roughness during hard turning. Therefore, research is required to investigate and analyse the dominance of individual parameters to assert the extent to which these have an effect on the attainable finish and quality of a machined surface.

3. Experimental details

To address the hypothesis that incorporating an SDM stage prior to conventional machining provides a superior quality of machined surface than that of the conventional HT operation, two sets of machining trials were performed under the same cutting conditions. In the first set of trials, the samples were machined using conventional hard turning only and in the second set they were machined using the SDM method. Additional trials were also performed to investigate the effect of changing the minimum feed rate. Specimens of AISI 4340 steel (69 HRC) were used as workpieces while CBN was used for the cutting tools. During the experimental trials, the feed rate was varied between 0.005 mm/rev to 0.08 mm/rev to determine the best feed rate associated with the best quality of machined surface. The reason for varying the feed rate only came from the prior knowledge and experience of the authors where it was observed that feed rate is by far the most dominant variable in influencing the machined surface roughness [42]. The execution of SDM was performed by firstly manufacturing surface defects in the form of holes on the top surface of the workpiece using a Trumpf (CO₂) laser machine with a peak power of 2.7 kW (figure 4a). The depth of hole was determined by parting-off the workpiece in the middle of the hole followed by an SEM examination (figure 4b). The extent of the surface damage induced by the laser drilling was observed to be minimal and it was ensured that this defect depth was covered by the programmed depth of cut. In actual fact, this damage feature depth is not of any real concern in practice because it can be recovered via the recrystallization process taking place during heat treatment, which is why SDM is particularly useful for machining hard steels.

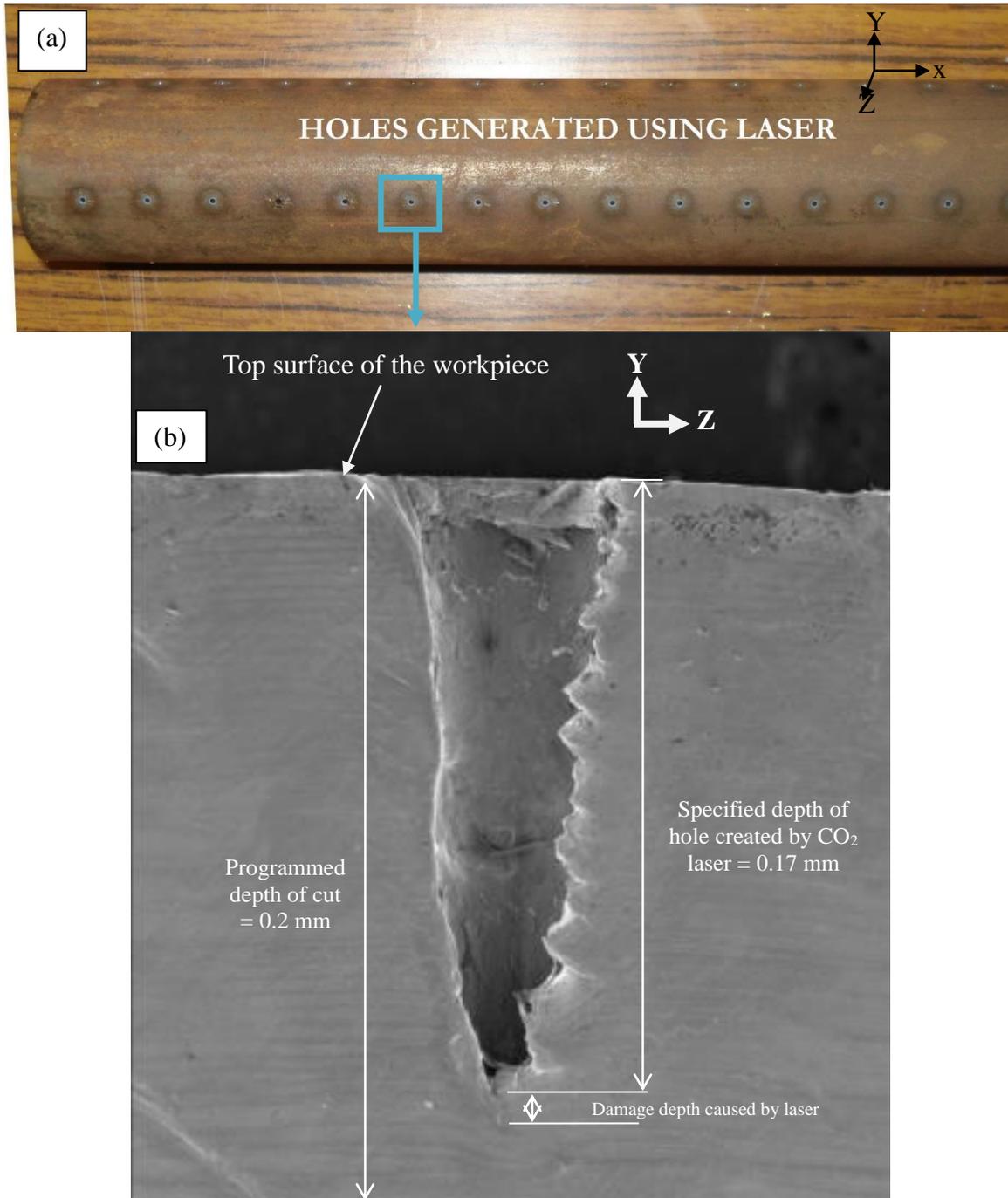


Figure 4: (a) Photographic image of the workpiece indicating manufactured surface defects created by the laser and (b) SEM image of the cross section of one of the surface defect created by CO₂ laser highlighting the damage depth caused by laser

Following the creation of surface defects in the form of holes, the machining trials were performed on a Mori-Seiki SL-25Y (4-axis) CNC lathe with Fanuc 18TC control [43, 44]. Some of the important specifications of this machine tool are spindle speed (RPM) range of 35-3500, maximum

cutting diameter of 260 mm, maximum turning length of 530mm, spindle motor power 15 kW, axial stiffness of about 1000-1500 N/ μm and radial stiffness of about 10,000-11,000 N/ μm for spindle and stiffness of slide being about 800 N/ μm . The cutting tool was procured from Warren Tooling Limited, UK (type CNMA 12 04 08 S-B). The cutting tool had a rake angle of 0° , clearance angle of 5° , and a nose radius of 0.8 mm. As stated before, since the intent of this work was mainly to evaluate the impact of the feed rate and to find its lower limit, only the feed rate was varied during the trials while the depth of cut and the cutting speed values of 0.2 mm and 90 m/min respectively were kept same in all the machining trials. The feed rate was varied from high to low (0.08 mm/rev \rightarrow 0.005 mm/rev) in both sets of experiments. Other details pertaining to the experimental set up, such as machining conditions and machining parameters are given in Table 3. Following the machining trials, a white light interferometer (Zygo NewView 5000), Form Talysurf and SEM (FEI Quanta3D FEG) were used to compare the surface topography and support the analysis of the machined surface.

Table 3: Experimental details and machining parameters

S.NO.	Details	Values
1	Workpiece Material	AISI 4340 steel hardened up to 69 HRC
2	Type of machining	Longitudinal turning trials
3	Diameter of the workpiece	28.8 mm
4	Cutting tool specifications (ISO code)	CNMA 12 04 08 S-B
5	Tool Nose radius	0.8 mm
6	Tool rake and clearance angles	0° and 5°
7	Feed rate used	0.005 mm/rev, 0.03 mm/rev and 0.08 mm/rev
8	Depth of cut	0.2 mm (was kept fixed in all trials)
9	Cutting speed	90 m/min (was kept fixed in all trials)
10	Coolant	None

11	Diameter and depth of holes (judiciously chosen)	0.9 mm and 0.17 mm respectively with 10 mm interspacing between each hole
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4. Results and discussions

4.1. Inspection of the machined surface

Figure 5 highlights the average variation in the measurement of the finish machined surface roughness, the average machined surface roughness (Ra) and peak to valley measurement (Rz).

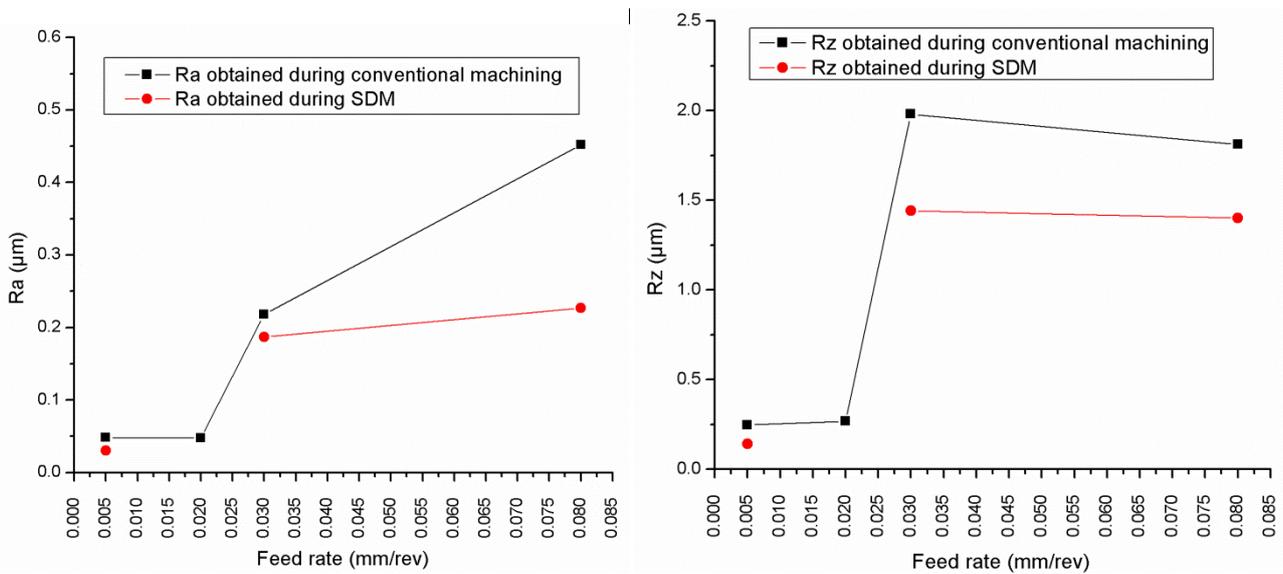


Figure 5: Variation in Ra and Rz with respect to feed rate during conventional machining and SDM

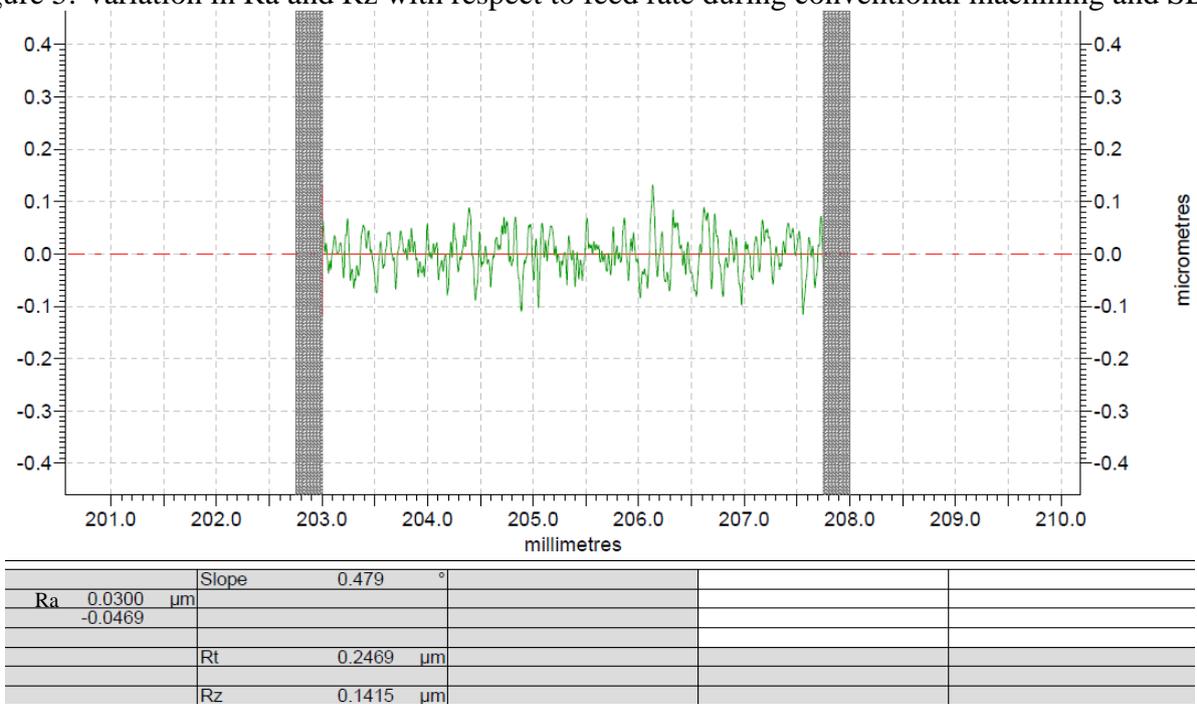


Figure 6: The average value of machined surface roughness of Ra 30 nm obtained on an AISI 4340 steel specimen machined using SDM

The plot in the figure 5 shows that a feed rate of 0.02 mm/rev is critical for attaining the best possible machined surface roughness using conventional hard turning method, indeed lowering of this value further to 0.005 mm/rev produced the same result i.e. Ra of 0.0478 μm . Compared to this value, the SDM method was able to provide a much better surface roughness of about Ra 30 nm which corresponds to the Form Talysurf measurement shown in Figure 6. This demonstrates that the critical feed barrier can be overcome by adopting the SDM method to obtain a better machined surface roughness. It means that SDM could potentially enable the accomplishment of a precision finish equivalent to that obtained by polishing and grinding process using conventional turning. Indeed, contrary to the earlier limitations reported by Konig *et al.* [45] where geometric tolerances corresponding to IT6 and the surface qualities of Rtm 2-3 μm are the maximum attainable, this research shows for the first time that IT4 is now achievable through state-of-the-art HT processing [1] using SDM. Of particular importance in this regard is the fact that the ASTM standard recommends the surface roughness value (Ra) on the metallic knee joint implants to be lower than 100 nm [46]; this was obtained with ease during this study. Furthermore, although ceramics such as silicon carbide are preferred choice over steels [47, 48] for such advanced biomedical applications, stainless steel is still used in practice and this work demonstrates that there is the potential to use hard turning to machine such precise components.

In order to gain even further insights into the process, the surface topographies of the machined surfaces obtained via classic HT (conventional machining only) and the SDM method were carefully studied. Figures 7 and 8 show this comparison for the final finished surface obtained in the two tests at a feed rate of 0.03 mm/rev. From this comparison, the P-V values obtained by the SDM method appeared much better than that obtained from classic HT.

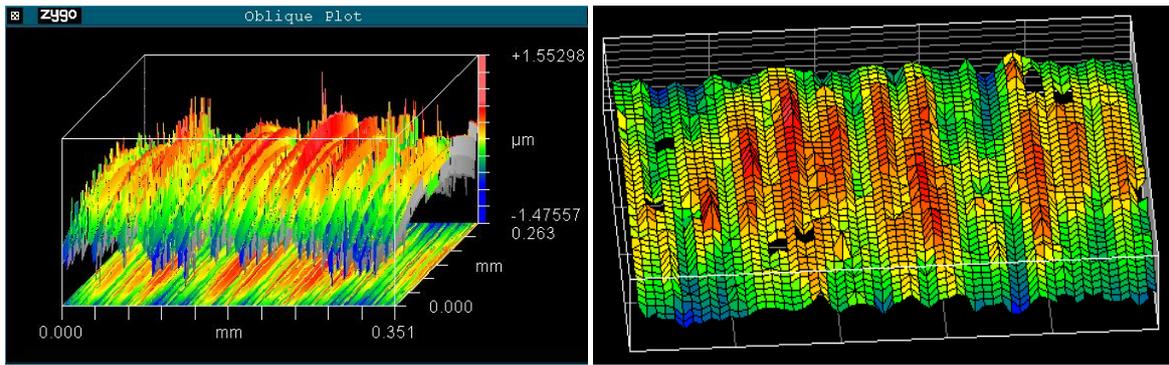


Figure 7: Topography of the machined surface obtained using SDM

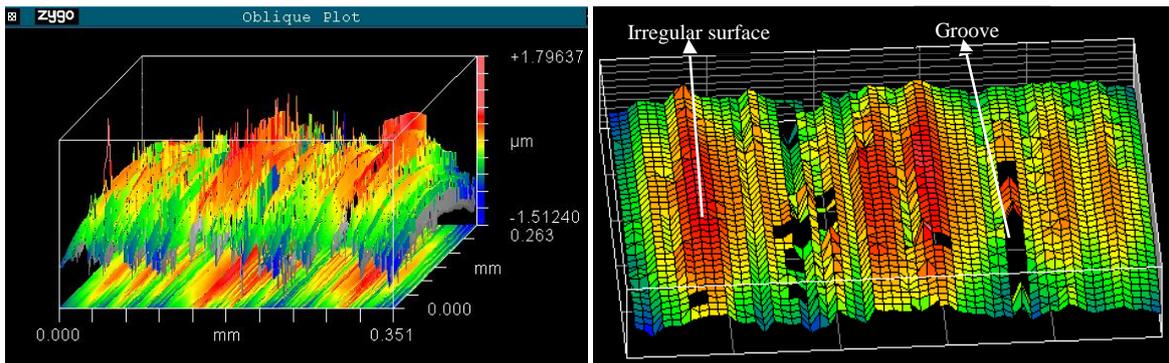


Figure 8: Topography of the machined surface obtained using classical HT

Other than the quantitative improvement in the surface roughness, a key difference observed was the presence of grooves, ridges and irregularities in the surface obtained via conventional HT whereas using SDM, a more uniform machined surface was obtained with minimum variation in the machined surface profile. This was further confirmed by carefully assessing the machined surface using SEM imaging shown in Figure 9 where the extent of pile-up and the occurrence of side flow during the SDM process were observed to be considerably reduced when compared to the classical HT approach, resulting in a better quality of machined surface roughness.

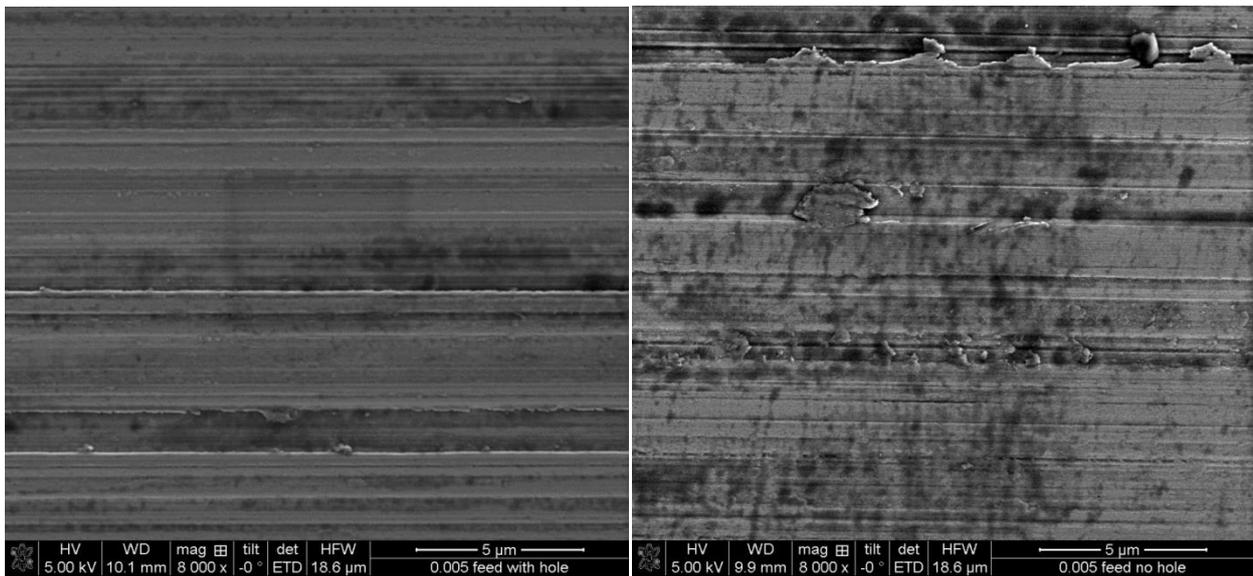
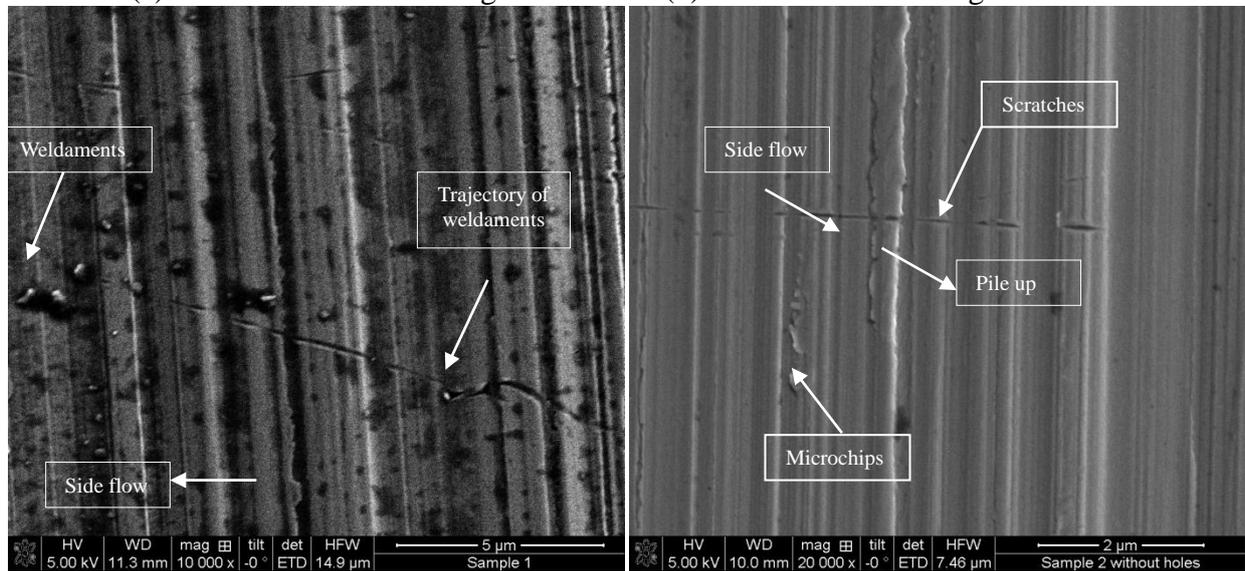
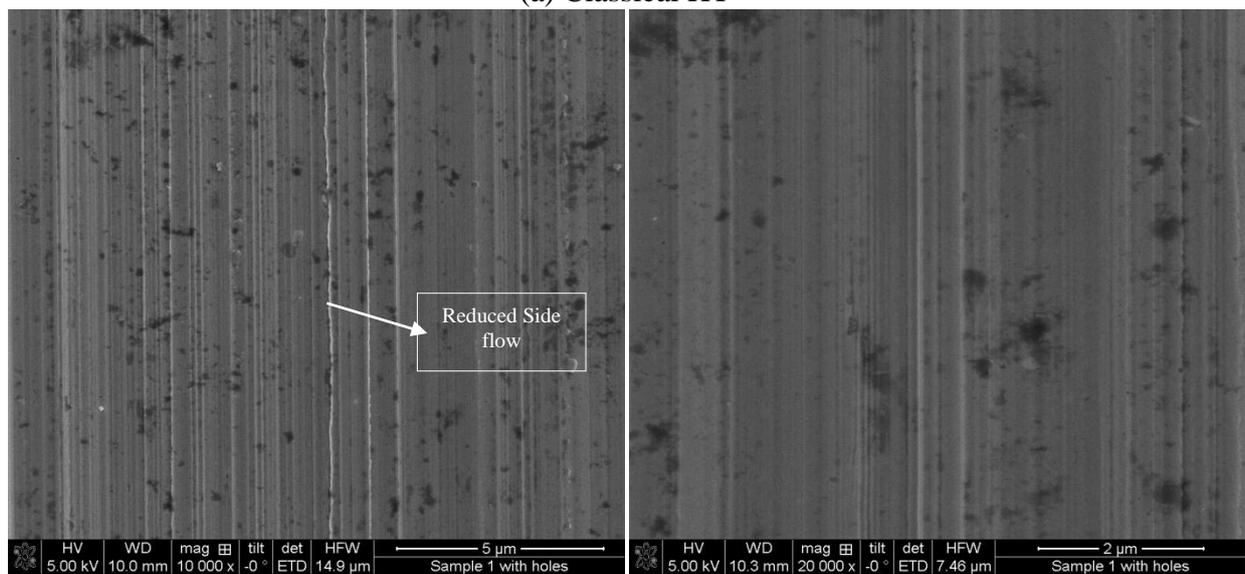


Figure 9: A comparison of the surface topography obtained via SEM under two different machining conditions: (a) surface defect machining method and (b) classical hard turning



(a) Classical HT



(b) SDM method

Figure 10: SEM examination of the machined surface qualities obtained from SDM

Figure 10 presents a comparison of the SEM images of the machined surface under the two machining conditions obtained from conventional HT and the SDM induced HT method. A significant difference between the qualities of the two machined surfaces is evident. Figure 10a reveals the appearance of several kinds of surface defects, e.g. excessive side flow, the presence of microchips on the machine surface, the presence of weldment particles and penetration of these particles in the machined surface forming scratches on the machined surface. As seen from the existing literature and this study, the post experimental SEM inspection of the machined surfaces obtained after conventional HT shows the appearance of all such surface defects which are precursor to the shortened service life of machined components. Contrary to this, the machined surface obtained from the SDM method showed a negligible extent of side flow and no considerable appearance of microchips on the finished surface. Another improvement observed from SDM was a reduction in the amount and appearance of the weldment particles. As discussed previously, small fractured edges of the steel subjected to an extremely high machining temperature in the cutting zone promote conditions for welding. The surface machined with SDM was found to be free from such weldments which in itself is an outcome of the reduced machining temperature during this SDM process [19].

4.2. Inspection of the white layer

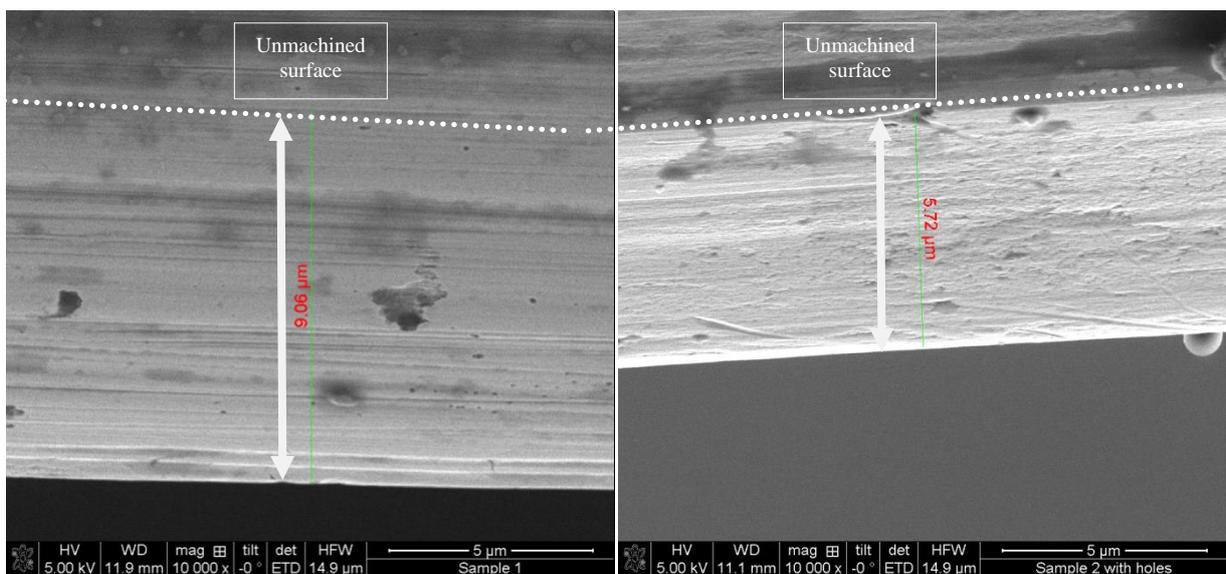


Figure 11: Measurement of white layer on the finished machined surface (a) Conventional HT (b) SDM induced HT

The formation and presence of white layer generated during classical hard turning has always been a limiting factor in the adoption of hard turning on the shop floor. It was therefore necessary to investigate whether or not the extent of white layer was affected by the use of SDM therefore SEM imaging was employed in accord with the traditional procedure [49]. Figure 11 compares the extent of white layer formation under the two test cases. The extent of the white layer measured in the classical HT specimen was $9.06\ \mu\text{m}$; this was substantially reduced to only $5.72\ \mu\text{m}$ in the SDM specimen signifying that SDM could reduce the metallurgical transformation on the surface during the machining process.

4.3. FEA analysis of the SDM

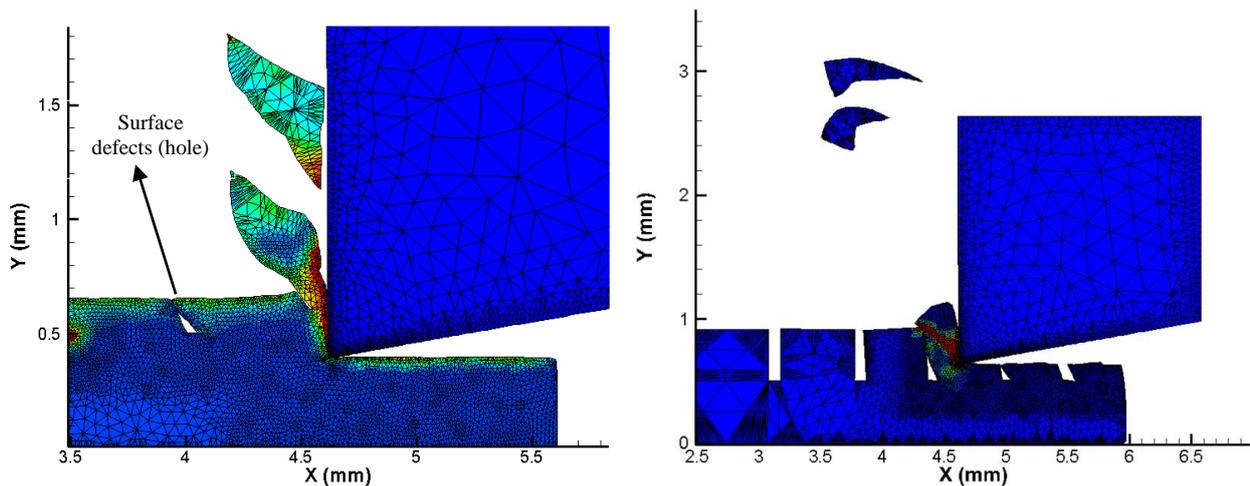


Figure 12: Finite element analysis of the surface defect machining of hard steel when the: (a) depth of surface defects is less than the depth of cut and (b) depth of surface defects is larger than the depth of cut

To further support the above experimental findings, an FEA was carried out to simulate the surface defect machining of AISI 4340 steel. These FEA simulations are in continuation of previously performed simulations, therefore the details of these are not repeated here for the purposes of brevity [23]. The results are shown for two cases where: (i) the depth of surface defects is less than the depth of cut and (ii) the depth of surface defect is more than the depth of cut. This enabled a more complete understanding of the whole process. The results in Figure 12 show the plastic strain during the machining. The most remarkable observation obtained from the FEA of SDM was a significant reduction in the shear plane angle due to a reduction in shear plane area during

machining. A decrease in the value of shear plane angle under the same machining parameters indicates the dominance of tangential cutting forces over thrust forces, which shows an enhanced cutting action of the tool. This means that for the same amount of energy input, the cutting action is considerably enhanced and the forces in the direction of the cutting velocity vector increases. Consequently, the deformation of the material occurs along the cutting direction and causes less side flow resulting in the improved machined quality of surface.

It is interesting to note that much of the previous research on hard turning has suggested using a feed rate in the range of 0.05 mm/rev to 0.2 mm/rev [2, 4]. The use of a higher feed rate is known to worsen the machined surface. Similarly, the use of feed rate beyond a certain lower critical limit also poses serious implications on the tool life, primarily due to ploughing between the cutting tool and the machined surface. The transition to ploughing during the cutting action could be a single important variable in determining the extent of minimum critical feed rate. Essentially, the conflict between the low feed rate and the width of the side flow influences the quality of the machined surface. The use of a feed rate as low as 0.005 mm/rev used in this work is not evident in the literature elsewhere and its successful implementation using the SDM method to achieve the Ra value of 30 nm is a major breakthrough in the history of hard turning. The part of this success may also be attributed to the quality of the CBN cutting tool tips and the developments in machine tools over the past decade.

5. Conclusions

The rapid advancement in instrumentation technology has made it possible to study various machining mechanisms at a much better spatial and temporal resolution than was previously possible. The application of white light interferometry and scanning electron microscopy to study how machined surface defects influence the microscopic mechanics of hard steel functional components and enable the evaluation of processes capable of producing optical quality surface finishes is a novel finding of this research. Based on the aforementioned results, the following conclusions may be drawn:

1. The quality of the machined surface generated by the conventional way of hard turning using conventional means is known to be limited by the feed rate. A lower feed rate is preferred to generate smooth surfaces but only up to a certain critical limit beyond which ploughing and consequent worsening of the machined surface become pronounced. The lowering of the feed rate beyond the attainable limit was realized to be a major breakthrough in achieving superior quality of surface finish on hard steels directly on a turret lathe by adapting the proposed surface defect machining (SDM) method.
2. Depending on the density of the manufactured surface defects, it is possible to realise significant improvement in the machinability of difficult-to-machine materials through a reduction in shear plane angle and shear plane area thus permitting reduced side flow with less metallurgical transformations on the finished machined surface and the sub-surface.

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