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Investigation of cutting forces, surface roughness and tool wear during Laser assisted machining of SKD11Tool steel

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Abstract

The present work deals with the machining of Tool steel - SKD 11 which is widely used in industries for making dies and molds. It is chosen for its toughness, strength, and hardness maintained up to high temperature. However, the properties of tool steel make it extremely difficult and expensive to machine using conventional approaches. Thermally assisted machining has been found wide spread application in recent years to improve machinability of difficult-to-cut materials. This research paper presents the outcome of an investigation on laser assisted turning of SKD 11 using TiN coated ceramic inserts. Extensive heating studies are carried out to understand the laser–material interaction. The LAM parameters were selected based on the outcome from heating study. In this study, the effect of laser beam on cutting forces, surface temperature, surface roughness and tool wear are analysed over wide range of cutting speeds and feed rate and the results are compared with conventional machining.

Keywords: SKD 11;laser assisted machining; material removal temperature; Nd:YAG laser;

1. Introduction

Hardened steels such as SKD 11 are widely used in automotive industries because of its excellent material properties. These materials are preferred for its unique metallurgical properties .Hardened steels are machined by using various advanced machining processes such as diamond grinding, electric-discharge machining etc. These methods were limited due to low material removal rate (MRR), expensive tool, high tool wear, time consuming and low surface finish [1-4]. This paves the way for the methods that will improve the machinability of these materials, whilst ensuring the preservation of their desired properties.

To reduce cutting force, tool wear and surface roughness, the thermally assisted machining technique has been investigated by various researchers. P.k.wrigh et al. [5] stated that in order to reduce the shear strength

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at the Cutting zone the workpiece surface temperature has to be elevated just below its re-crystallization temperature. This would eliminate the problems arises due to low cutting speeds, feeds, and heavy loads and makes the machining easier. Mukherjee et al. [6] carried out statistical evaluation of metal cutting parameters in hot machining in order to reduce vibration, surface roughness, and tool wear. They found that temperature, rather than cutting speed, had more dominant effect on reducing surface roughness. They claimed that preheating increased the ductility of the work material, which was conducive to chip formation and flow. Mahdavinejad [7] stated that power consumption during turning was primarily required in shearing and plastic deformation of the work-piece for metal removal purposes. Since, both shear strength and hardness of most materials decrease with increasing temperature, he noted that an increase in the work-piece heating temperature would reduce the power consumed for machining as well as the stresses acting on the tool.

In TAM the work materials are preheated by an external energy source upto softening temperature and then machined by conventional processes. The preheating reduces the tensile strength, hardness and strain hardening of work material. The various heat sources such as oxyacetylene torches, induction coils, plasma and laser are used by various researchers and reported that plasma and laser are the proficient heating source for TAM. Laser beam can be used as a tool supporting or assisting a cutting process to increase the process efficiency or simply to enable a cutting process of materials with difficult cutting properties [8-11].

In laser assisted machining, the intense energy of laser was used to enhance machinability by locally heating the workpiece and thus reducing yield strength [12]. kim et al [13] analysed and reviewed about the recent trends in research and development of laser assisted turning. Attia et al. [14] compared the material removal rate with laser assisted finish turning and conventional machining. He found that the surface finish was improved by 25% and material removal rate was increased by eighty times approx. The instantaneous heating capability of laser with focused beam is ideally suited for the material difficult to process by mechanical machining. Hence the laser has been considered as an effective heating source for thermally assisted machining of hard materials.

Depending on the material to be processed, the laser beam power intensity, the spot size, the beam distribution, and the scanning velocity has to be optimised [15-20]. A series of experiments were designed for analyzing the effect of laser parameters and cutting parameters through preheating study and laser assisted machining of SKD 11. The main objective of this paper is to analyse the machining output variables such as cutting force, surface roughness and tool wear over a wide range of laser parameters when machining SKD11 tool steel with the assistance of laser beam.

2. Experimental procedure

2.1. Workpiece material

The workpiece material used for present LAM study is SKD 11 tool steel material in the form of round bar of 26 mm diameter and 150 mm length. It is suitable for making press molds, tools and dies. The hardness of as received workpiece was found to be 45± 1 HRC. It has been hardened to 61±1 HRC. The chemical composition of SKD 11 is tabulated in Table 1.

Table 1 Chemical composition (wt%) of SKD 11

Elements	C	Si	Mn	P	S	Cr	Mo	V
%	1.42	0.30	0.41	0.025	0.0004	11.70	0.83	0.23

2.2. Experimental setup

A precision high speed lathe which was manufactured by ‘Gedee Weiler’ (MLZ 250 V) was used to perform machining trails. A 2 kW Nd:YAG continuous wave laser of wavelength 1.06 µm was used to preheat the SKD 11 workpiece. The laser source was delivered through an optical fiber cable of 15 m long to a focusing head with focal length of 160 mm. A special fixture was designed and fabricated in order to hold the laser head and pyrometer in line with the lathe machine in such a way that the laser beam can be precisely positioned on the workpiece surface at an angle of incidence of 75°. Compressed air at 4 bar was used to protect the laser optics from the fumes and debris resulting from the heating and cutting processes. The surface temperature was measured using an online dual wavelength Williamson pyrometer of range between 500 and 2000^{o} C for all the trails. A Kistler dynamometer (9257B) with charge amplifier was mounted on the tool post to measure the cutting forces .The Mahr surface roughness tester was used to measure the surface characteristics of the machined workpiece. The tool wear was measured using Carl zesis optical microscope. Figure1 illustrates the experimental set up developed for the laser assisted machining of SKD 11. This study consists of two phases that is preheating phase and laser assisted machining phase.

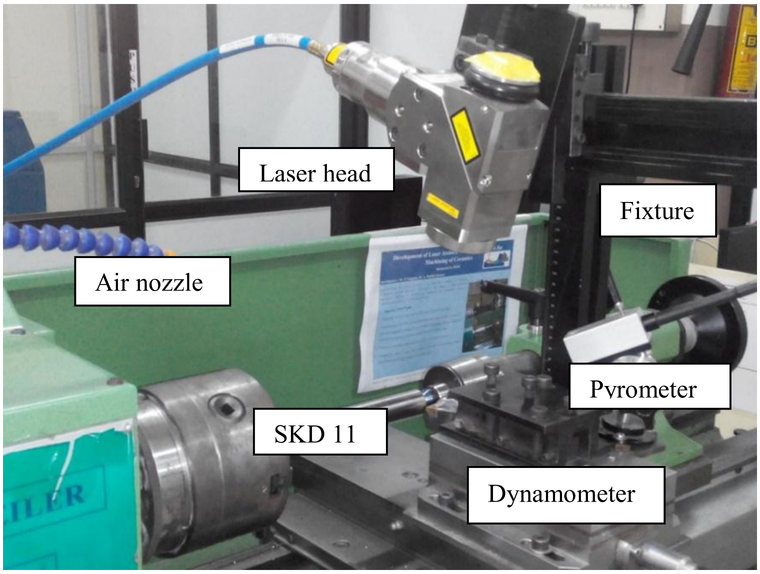

Figure 1 Photograph of laser assisted machining setup

2.3. Laser heating experiments

The laser pre heating experiments were performed for SKD11 by varying the laser power, spot size, pre heating time, cutting speed and feed rate. The factors and their levels chosen for the heating study are shown in Table 2. The detailed experimentation plan is shown in Table.3 to study the effect of laser parameters and machining parameters on surface temperature. The heating experiments were performed for a length of 60mm and 26 mm diameter rod. It was observed that when the laser strikes the material during the pre-heating time, there is a sudden rise in surface temperature after that the temperature reduces to steady state temperature because of heat absorption of material. For the Trails (1-3), the laser power was varied and it has been observed that the higher the laser power, the higher the surface temperature due to absorption of more heat energy into the work piece. For the trails (4-6), the smaller beam spot size gives higher temperature due to higher laser intensity. For the trails (7-9), as the cutting speed increases the laser to material interaction time is less and ultimately it leads to low elevated surface temperature. For the Trails (10-12), as the feed rate decreases, more heat energy is deposited in the workpiece which results in higher temperatures. For trails (12-15), the preheating time is used to elevate the temperature at cutting zone. It was found that pre heating time is inversely proportional to laser power. Higher laser power will require lesser preheating time. Based on the heating experiments, it was observed that the laser power, cutting speed and feed rate had more influence in elevating the surface temperature .The temperature data were recorded for all the trails with respect to time and typical plot is shown in Figures 2. The results obtained from the thermal study gives a clear guideline for choosing the parameters for LAM.

Table 2 Factors and their levels

Factors	Level1	Level2	Level3
Laser power(W)	750	1000	1250
Spot size(mm)	1	2	3
Pre heating time(sec)	5	8	11
Cutting Speed(m/min)	75	100	125
Feed rate(mm/rev)	0.05	0.075	0.1

Table 3 Operating conditions for laser preheat studies and average surface Temperature

Expt. No	P (W)	Spot size (mm/min)	Cutting speed (m/min)	Feed rate(mm/rev)	Preheat (sec)	Avg. surface Temperature(°C)
1	750	2	100	0.075	8	550
2	1000	2	100	0.075	8	680
3	1250	2	100	0.075	8	1050
4	1000	1	100	0.075	8	950
5	1000	2	100	0.075	8	700
6	1000	3	100	0.075	8	550
7	1000	2	75	0.075	8	970
8	1000	2	100	0.075	8	670
9	1000	2	125	0.075	8	520
10	1000	2	100	0.05	8	780
11	1000	2	100	0.075	8	570
12	1000	2	100	0.1	8	500
13	1000	2	100	0.05	5	730
14	1000	2	100	0.05	8	810
15	1000	2	100	0.05	11	1090

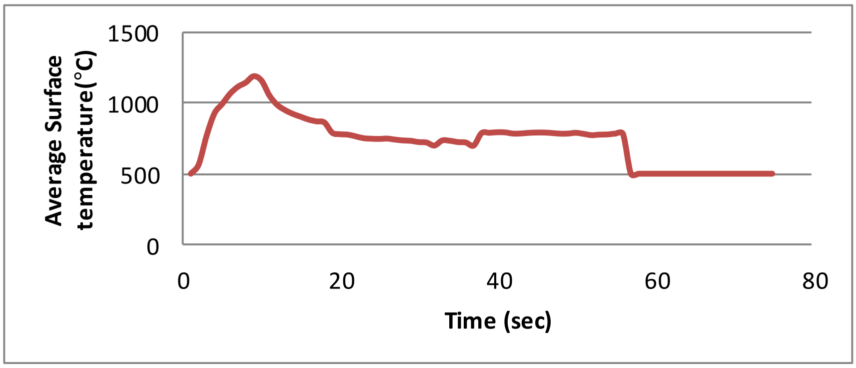

Figure 2 Surface temperature variations along the heating length for trail 13

2.4 Machining trails

To better understand the effect of machining performance and obtain optimum cutting conditions, various experimental trails were performed under a wide range of cutting speeds and feed rates. The key laser parameters such as laser power, spot size and lead distance were chosen based on the preliminary heating studies conducted on SKD 11.The LAM tests were carried out for a length of 30mm. The test was performed under two sets of cutting conditions. In the first set of experiments, the feed rate is kept constant and the cutting speed is varied from 80 to 140 m/min. as shown in Table 4 (Trails 1-4). In the second set of experiments, the cutting speed was kept constant and feed rate was varied from 0.03 to 0.1 mm/rev as shown in Table 4 (Trails 5-7). In all these experiments, the laser power of 1000 W, spot size of 2 mm, lead distance of 2 mm was used. During each experiment, cutting force was measured using Kistler dynamometer. The machining trails were carried out by using PVD coated ceramic tool (TiN) CNGA 120408E (grade KY4400, made by Kenna metal). A new cutting insert was used for each trail and the surface roughness values were measured for each specimen in 3 locations and the arithmetic surface roughness average was taken in to consideration. The experimental matrix for LAM of SKD 11 and their output responses are shown in the Table 4.

Table 4 Experimental matrix and output responses for LAM

Ex. no	P (W)	Cutting speed (m/min)	Feed rate (mm/rev)	DoC (mm)	F(x)N	F(y)N	F(z)N	Avg. temperature(°C)	Tool wear(μm)	Ra(μm)
1	1000	80	0.05	0.5	18	38	36	905	15	0.6
2	1000	100	0.05	0.5	16	33	31	740	13	0.45
3	1000	120	0.05	0.5	25	58	44	635	25	0.55
4	1000	140	0.05	0.5	32	64	52	550	33	0.62
5	1000	100	0.03	0.5	18	30	28	710	10	0.28
6	1000	100	0.07	0.5	25	53	50	650	17	0.64
7	1000	100	0.1	0.5	28	62	57	520	23	1.2
8	0	100	0.03	0.5	56	78	58	n/a	54	0.42

3. Results and discussion

3.1. Effect of cutting speed on cutting forces, temperature, tool wear and surface roughness

To obtain the optimum conditions in terms of cutting speed, a series of tests were designed with increasing cutting speed as shown in Table 4 (1-4 trails). In these experiments, the feed rates, depth of cut and laser power were kept constant. The cutting speed was varied between 80 to 140 m/min and the corresponding cutting forces, average temperature, surface roughness and tool wear were measured. The results for the cutting force measurements are represented in Figure.3. It has been observed, that when increasing the cutting speeds, initially there is a rise in force and then it drops for 100 m/min and beyond which gradually starts to increase. The forces were minimum for cutting speed of 100 m/min as illustrated in the Figure 3. This means that further increase in cutting speed does not affect the forces significantly due to the fact that higher cutting speeds result in poorer absorptivity of laser power. It has been observed that radial force is dominating force than the cutting force.

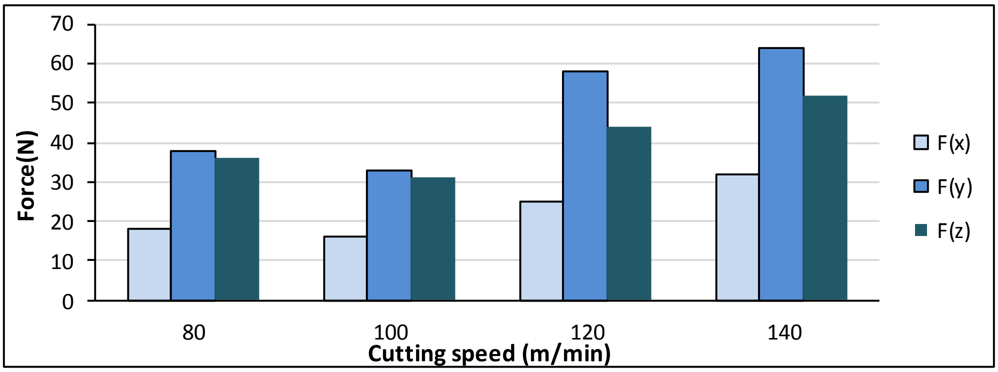

Figure 3 Cutting forces for different Cutting speeds

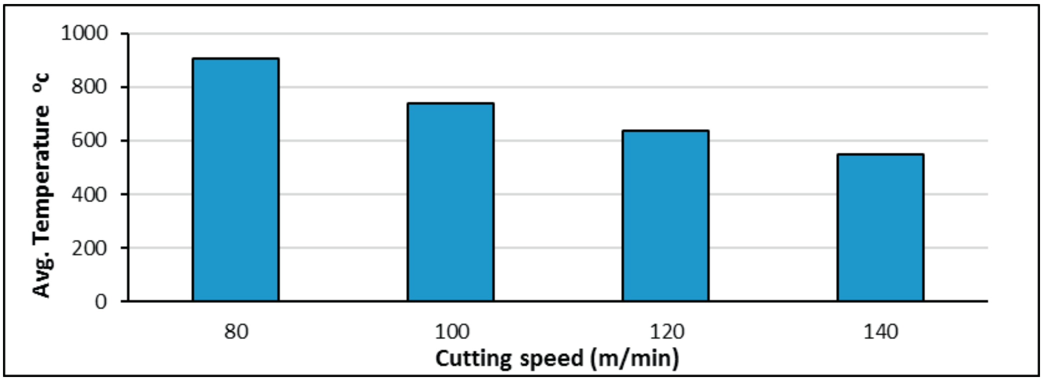

Figure 4 Average temperature for different Cutting speeds

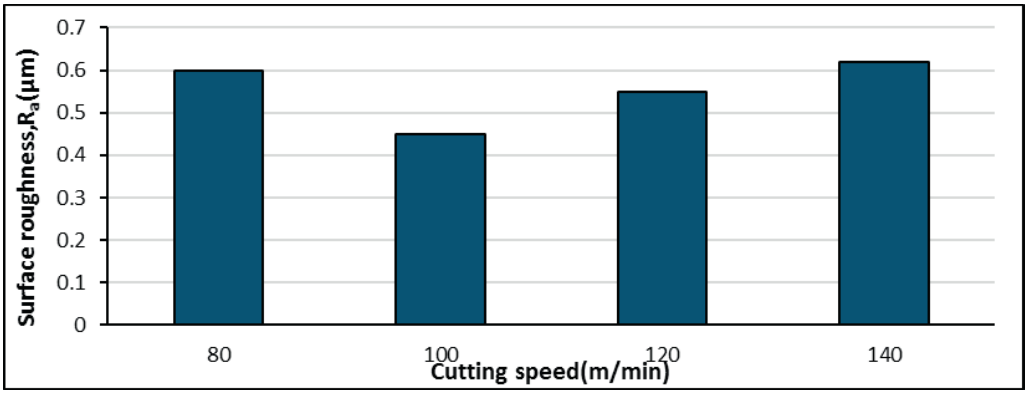

Figure 5 Average roughness for different Cutting speeds

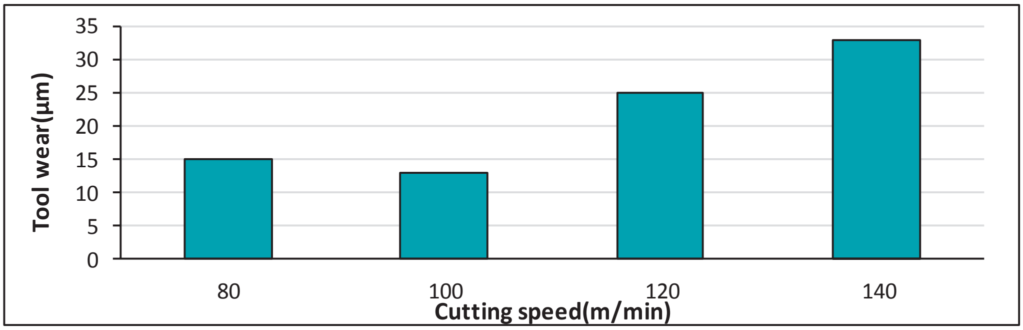

Figure 6 Tool wear for different Cutting speeds

The effect of cutting speed on average surface temperature is depicted in Figure 4. The results indicate that the surface temperature decreases with the increase in cutting speed. This is due to the less time available for laser–material interaction which resulted in low surface temperature. Surface roughness was measured for various cutting speeds. The effect of cutting speed on surface roughness is shown in Figure.5. It was observed that, increase in surface roughness is related to increase in tool wear. It has been found that, as cutting speed increases from

100 m/min there is an increase in average flank wear. There were no signs of crater wear or excessive wear on rake face for all cutting speeds due to small cutting length as shown in Figure 6. Based on the output responses, it was found that, for a cutting speed of 100m/min exhibits lowest cutting forces, surface roughness and tool wear. The LAM test for optimum feed rate was carried out using the cutting speed of 100 m/min.

3.2. Effect of feed rate on cutting forces, surface roughness, temperature and tool wear

To obtain the optimum conditions in terms of feed rate, a series of tests were designed with increasing feed rate as shown in Table 4 (5-7 trails). For all these experiments, the cutting speed, depth of cut and laser power was kept constant. The feed rates were varied between 0.03 to 0.1 mm/rev and the corresponding cutting forces, average temperature, surface roughness and tool wear were measured. The results for the cutting force measurements are represented in Figure.7. It has been observed, that when increasing the feed rate, there is a steady rise in all three component of forces. The forces were minimum for feed rate of 0.3 mm/rev as illustrated in the graph. This means that further increase in feed does not affect the forces significantly due to the fact that more material to be removed per revolution and also higher feed rates result in poorer absorptivity of laser power. The effect of feed rate on average surface temperature is depicted in Figure 8. The results indicate that the surface temperature decreases with the increase in feed rate. It was found that increasing feed rate does not cause a significant increase in cutting zone temperatures due to the less time available for laser power to be absorbed in the material. Surface roughness was measured for various cutting feeds. The increase in feed rate increases surface roughness is shown in Figure 9. This is due to distinct feed marks produced by the cutting edge. As the feed rate increases there is a little or no thermal softening occurs after the feed rates of 0.03 mm/rev which leads to more tearing and high surface roughness. It was also noted that, as the feed rate increases there is no significant impact with respect to tool wear. There is no appreciable tool wear for all feed rates due to small cutting length. It was clearly depicted in the Figure 10, the trends of flank wear with respect to feed rate.

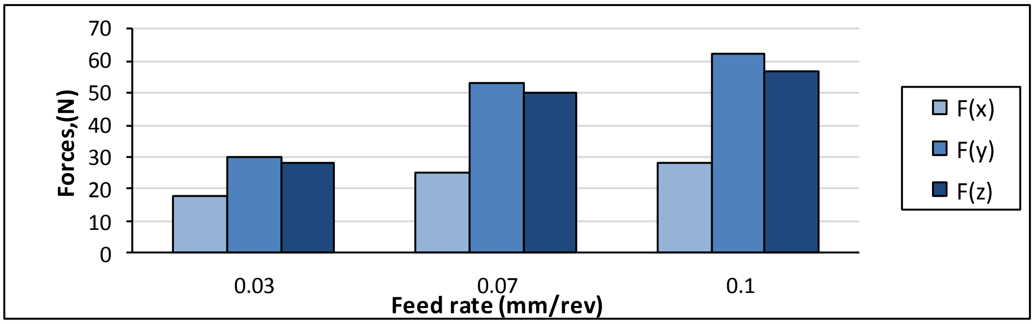

Figure 7 Cutting forces for different Feed rates

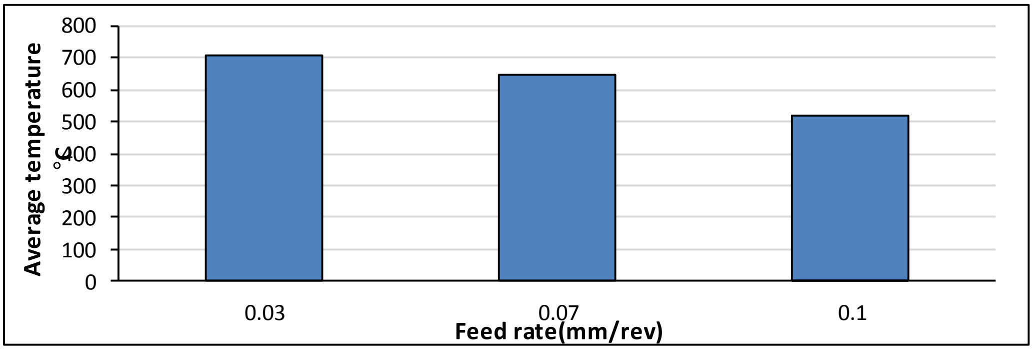

Figure 8 Average temperature for different Feed rates

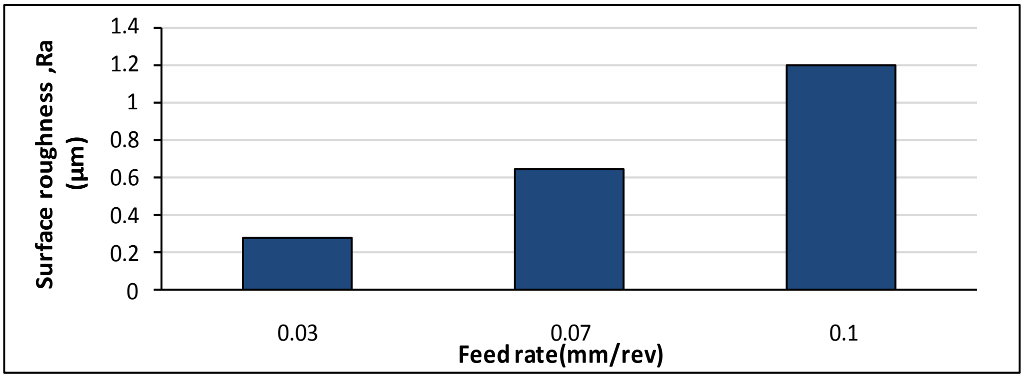

Figure 9 Surface roughness for different Feed rates

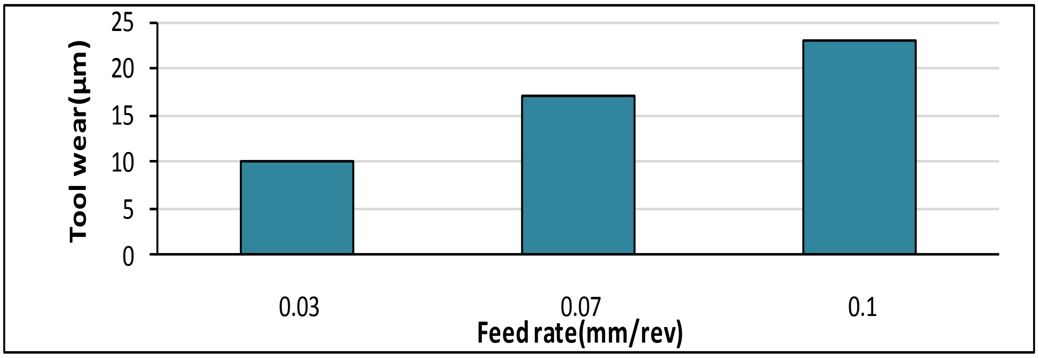

Figure 10 Tool wear for different Feed rates

3.3. Comparison of LAM Vs Conventional machining

In order to compare the LAM with conventional machining an additional experiment (Expt. 8) was performed at the machining conditions corresponding to the lower forces in LAM without laser heating. The average cutting force reduction of about 40% was observed for LAM when compared to conventional machining and is shown in Figure 11 (a) & (b).

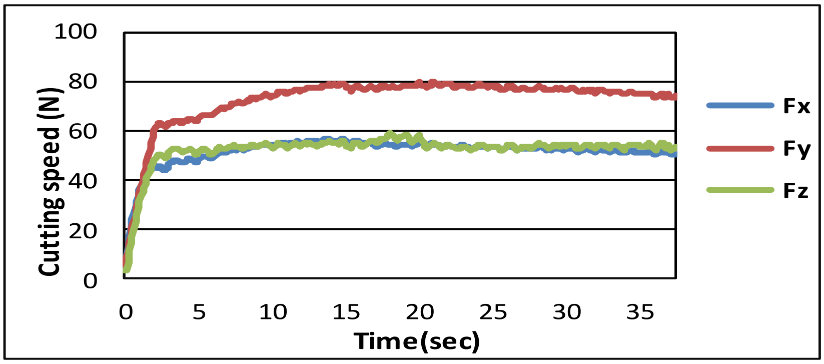

Figure 11 a) Cutting force for convectional machining at 100mm/min.

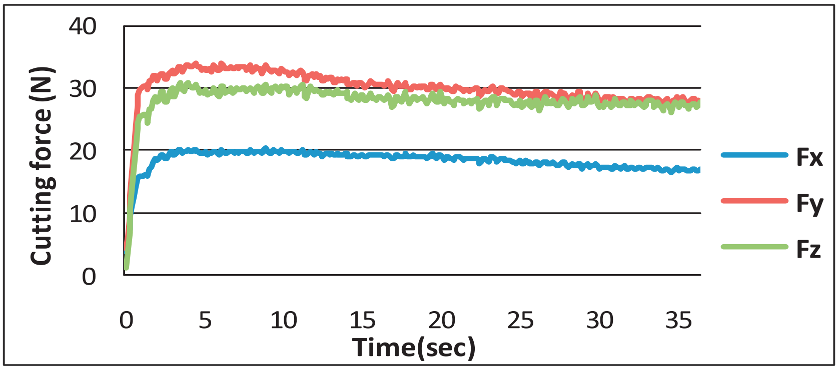

Figure 11 b) Cutting force for LAM at 100mm/min.

There is 50% increase in surface roughness when compared to conventional machining as shown in Figure 12. It was observed that the flank wear rate is very less when compared to conventional machining and notch wear is absent is shown in Figure 13. Thus, it is very evident that the surface temperature plays major role on cutting forces, surface roughness and tool wear in LAM.

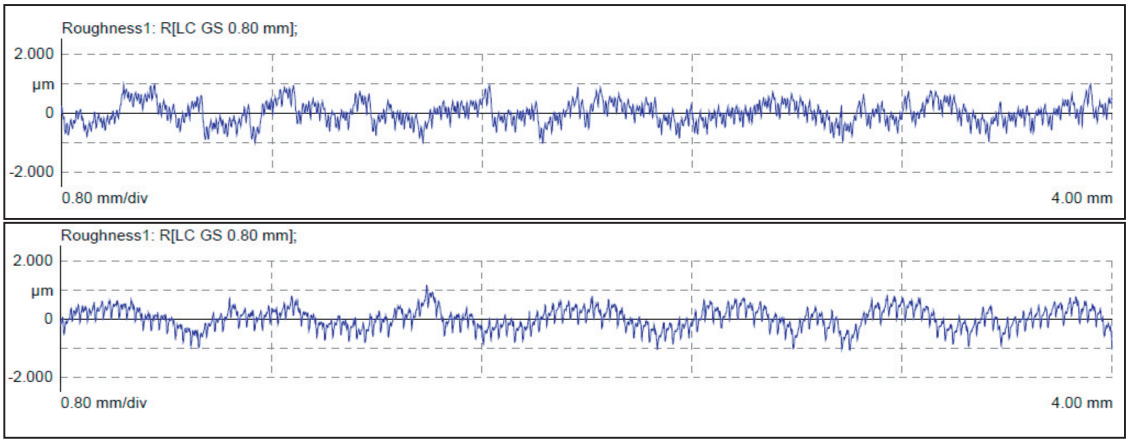

Figure 12 a) Surface roughness for convectional machining at 100mm/min. b) Surface roughness for LAM at 100mm/min

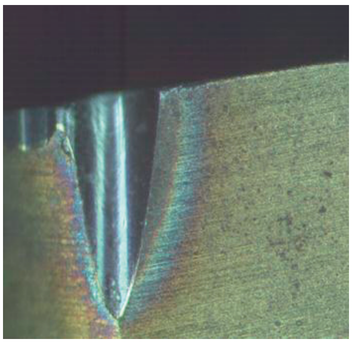

Figure 13 a) Tool wear for conventional machining 100x

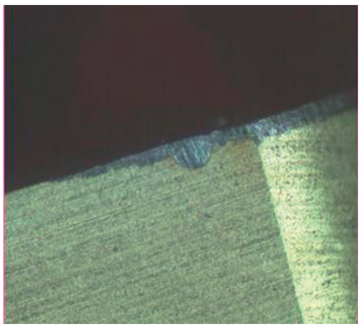

Figure 13 b) Tool wear for LAM 100x

4. Conclusions:

The main objective of this paper is to study the potential of LAM for SKD 11 material. The following conclusions were drawn from the above experimental results.

- The surface temperature of the SKD 11 material increases with the increase in laser power and decrease with increase in machining parameters.
- The minimum cutting force is observed during LAM at laser power of 1000 W and cutting speed of 100 m/min and feed rate of 0.03 mm/rev.
- It was observed that force reduction of about 40% for LAM at identical machining conditions when compared to conventional machining.
- The surface temperature can be maintained around 600-750 ^{o}C for better machining.
- The surface roughness was improved 50% when compared to conventional machining.

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