Fundamental investigation on influence of external heat on chip formation during thermal assisted machining

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Abstract. Various heat sources have been investigated by numerous researchers to reveal machinability benefits of thermally assisted machining (TAM) process. Fewer engineering materials have been tested. In the same vein, those researches continue to demonstrate effective performance of TAM in terms of bulk material removal rate, improved surface finish, prolong tool life and reduction of cutting forces among others. Experimental investigation on the strain-hardenability and flow stress of material removed with respect to increase in temperature in TAM has not been given attention in previous studies. This study investigated the pattern of chip morphology and segmentation giving close attention to influence of external heat source responsible for strain – hardenability of the material removed during TAM and dry machining at room temperature. Full immersion down cut milling was used throughout the machining conditions. Machining was conducted on AISI 316L using uncoated tungsten carbide end mill insert at varying cutting speeds (V) of 50, 79, and 100 m/min, and feed rates (f) of 0.15, 0.25, and 0.4 mm/tooth while the depth of cut was maintained at 0.2mm throughout the machining trials. The analyses of chip formation, segmentations and stain hardenability were carried out by using LMU light microscope, field emission microscopy and micro indentation. The study observed that build up edge is formed when a stagnation zone develops in front of tool tip which give rise to poor thermal gradient for conduction heat to be transferred within the bulk material during dry machining. This promotes varying strain – hardening of the material removed with evident high chips hardness and thickness, whereas TAM circumvents such impairment by softening the shear zone through local preheat.

1. Introduction
Recent studies undertaken on thermally assisted machining (TAM) have widely investigated various machinability factors but the phenomenological approach of investigation of chips formation received little attention to several researchers. Previous investigations reported by Alkali et al [1] have shown that the causes of variation of chips morphology can depend on the workpiece and cutting tool material and cutting conditions among other parameters. The formation of chips during metal cutting is further described by many scholars, including Ning et al [2] and Kovac and Sidjanin [3]. In another development, Yang and Lei [4] investigated chip morphology while cutting silicon nitride ceramic using laser assisted machining (LAM). Their investigation revealed semi continuous chips with...
various lengths that have been obtained at preheat temperatures of 1480°C and 1595°C. They further reported that larger chip dimensions indicate bigger plastic deformation. Their investigation did not report the morphological segmentation of the chips produced during the cutting process. Sun et al [5] reports that the chips thickness and serration in conventional milling was higher and presents cutting instability when compared to machining at elevated temperature (TAM) using laser beam as a heat source during milling titanium alloy (Ti-6Al-4V). Ding et al [6] study the chip formation and temperature effect on titanium alloy workpiece. Their report revealed that deformed chip thickness grew thicker during the initial 30μs cutting time irrespective of the parametric dimension of the undeformed chip thickness. Amin et al [7] reported that chips produced during TAM on carbon steel are more elongated and thinner than those obtained while conventional machining at room temperature. They described this occurrence to lower cutting forces and stresses on the cutting tool during the heat assisted machining. This significantly influences machinability benefit in terms of lower vibration and tool wear. The impulse of the present investigation is the formation of serrated chips reported in various TAM studies Viharos et al [8]. Currently, there is lacking literatures on chips formation of 316L stainless steel during TAM with oxyacetylene flame as a heat source mechanism. As a result, this research is aimed to reveal the mechanism involve in the chips formation during end milling 316L stainless steel using uncoated WC-Co insert. In particular, the study investigated the pattern of chip morphology and segmentation giving close attention to influence of external heat source responsible for strain – hardenability of the material removed during TAM and dry machining at room temperature.

2. Oxyacetylene as a Heat Source in TAM
The oxyacetylene gas flame has high penetration to width ratio. This enables its penetration into thicker work piece by using a single pass. These potentials make it suitable for use as heat source in TAM. Previous researches like the work of Davami and Zadshakoyan [9] and Mukherjee and Basu [10] have shown the feasibility of using TAM in terms of machinability improvement like longer tool life and improved surface finish using oxyacetylene as a heat source. Whereas the latter reported significant machinability improvement, the former reported that about 15% reduction of yield stress was experimentally observed while cutting AISI 1060 steel on centre lathe. These researchers concluded that tool life increment during thermally assisted machining is due to decrease of the yield stress of the work material. Interestingly, the mixed gas flow rate that eventually produces oxyacetylene heat flux can numerically be quantified. The flow rate of oxygen and acetylene gases should individually be determined. This gives the ability over thermal control of the heat source which has been a major challenge in TAM. Details of oxyacetylene parametric control could be obtained from Alkali et al [11]. It may be interesting to note that ability to control heat source in TAM process eliminates the tendencies for undesirable structural changes in the workpiece and improves machinability.

3. Experimental Set up
Machining was conducted on AISI 316L using uncoated tungsten carbide end mill insert at varying cutting speeds (V) of 50, 79, and 100 m/min, and feed rates (f) of 0.15, 0.25, and 0.4 mm/tooth while the depth of cut was maintained at 0.2mm throughout the machining trials. RSM technique was used to design the machining tests conducted both at room temperature and at elevated temperatures, in order to achieve valid and reliable conclusions in an effective and economical manner. The workpiece material composition is presented in Table 1.

Table 1. Nominal Composition of 316L Austenitic Stainless Steel

| C  | Mn  | Si  | P   | S   | Cr  | Mo | Ni  | N   | Fe |
|----|-----|-----|-----|-----|-----|----|-----|-----|----|
| 0.03 | 2.00 | 0.75 | 0.045 | 0.03 | 18.67 | 3.16 | 10.00 | 0.10 | Bal |
The typical cutting tool signature of uncoated WC-Co insert is given in Figure 1. The inserts have neither a hole nor chip breaker.

![Figure 1. Signature of Uncoated WC-Co Insert](image)

The samples have been sized 60mm x 50mm x 12mm with non-conventional electric discharge machining (EDM) wire cut using wire size of 0.25mm and tensile strength of 1000N/mm². Experimental trials were obtained by using response surface (RSM) design to investigate the influence of external heat source responsible on segmentation and strain – hardenability of the formed chips during TAM and dry machining at room temperature. Full immersion down cut milling was used throughout the machining conditions in which the end teeth of the tool are predominantly used on Excel FU 281 universal milling machine. The universal milling machine has main drive spindle speed in the range of 40 – 2000 rpm. It has table work surface of 300 x 1250mm. The table can swivel to left and right of 45 inch. The table moves longitudinally traverse: 845mm, crosswise traverse: 230mm and vertically traverse: 390mm. ME-40TMT3x12 type cutter with 40mm diameter and three insert slots was used to securely hold one uncoated WC-Co insert at a time. The experimental set up is shown in Figure 2.

![Figure 2. Typical TAM Set up with WC-Co Insert Secured on 40mm End Mill Cutter](image)
3.1. Chips Preparation

Induced temperature during TAM was recorded using T640 Flir thermal image camera with program version 1.2. The objective of incorporating the thermal imager is to accurately examine the impact of external heat during preheat with oxyacetylene so as to identify specific preheat range associated with morphological segmentation and strain hardenability of the produced chips. The chips that have been produce from end milling 316L stainless steel have been collected and analyzed by using digital camera, optical microscope and scanning electron microscope (SEM). The chips have been prepared for microscopic investigation by hot mounting using Buehler SIMPLIMENT 1000, followed by grinding polishing and etching to be able to reveal the structural details of the chips. From the successive investigations, micro indentation, chip thickness, chip forms and chip serration have been critically studied to report their influence on the machinability of 316L stainless steel during TAM and conventional machining at room temperature. Chip images were captured with Leica light microscope using 100X magnification to study different segments of the chips produced and justify scientific hypothesis.

3.1.1. Machining Variables

The selection of the variables is restricted within the machine specifications except for the axial depth of cut. This study used three different ranges of both cutting speed and feed while the axial depth of cut was kept constant at 1mm as shown in table 2. Other heat source components like heat source height, lead distance mixed gas pressures are also kept constant except for the speed of the travelling heat source (in case of TEM).

| S/N | Parameters                      | Range  |
|-----|---------------------------------|--------|
| 1   | Cutting Speed (m/min)           | 50 79 100 |
| 2   | Feed (mm/tooth)                 | 0.15 0.25 0.4 |
| 3   | Heat source Height (mm)         | 7.5    |
| 4   | Lead Distance (mm)              | 40     |
| 5   | Acetylene gas Pressure (Psi)    | 10     |
| 6   | Oxygen gas pressure (Psi)       | 25     |

4. Result and Discussion

Investigations were conducted on the chips formed during end milling cutting. The chips were collected, prepared through grinding, polishing and etching. The scanning electron microscopy (SEM) was used for micro-examination of the structured morphology. Lengthwise micro-sections of the chips at various cutting conditions were identified and viewed under the optical microscope to capture the structure of the chip and also examined the nature of primary and secondary serrated elements within a given length of the chips.

Accordingly, the chips obtained during the entire investigations are evaluated based on ISO 3685 classifications and the chips micrographs were examined to identify the following effects;

1. If the chip is burned or melted.
2. If the chips edges are rough or have straight edges in the cutting direction.
3. The morphology of the chips.
4. The chip serration

Micro sections of chips at stated selected cutting speeds are shown side in Figure 3 for TAM and conventional cutting at room temperature. It was generally observed that the 316L stainless steel (SS)
chips are characterized with primary and secondary serrated teeth formed as a result of the adiabatic shear process. The study found out that built-up edge was formed when a stagnation zone develops in front of the tool tip during machining at room temperature condition while end milling at cutting speed \(V=50\text{m/min}\) and \(f=0.4\ \text{mm/tooth}\).

| Room Temp. Machining |
|----------------------|
| ![Image](chips1.png) |
| 20\(\mu\text{m}\) Mag. 100X |

| TAM |
|-----|
| ![Image](chips2.png) |
| 20\(\mu\text{m}\) Mag. 100X |

**Figure 3.** Micrograph of Chips Produced at 120seconds Cutting Time \(V=50\text{m/min}\) \(f=0.4\text{mm/tooth}\) while Machining at Room Temperature and Thermally Enhanced Machining at 253°C

Generally, chips generated during machining at room temperature conditions are characterized with saw tooth shape, implying instability during the cutting. The serrations of the chips in this regard are mostly stable secondary type. It was believed that the serration was developed when the shear plane rotates in the direction of reduction of the shear angle during the phase of compression stages. Konig [12] concluded that the chip is formed by cracking and plasticisation as a result of high compressive stresses occurring from negative cut.

| Room Temp. Machining |
|----------------------|
| ![Image](chips3.png) |
| 20\(\mu\text{m}\) Mag. 100X |

| TAM |
|-----|
| ![Image](chips4.png) |
| 20\(\mu\text{m}\) Mag. 100X |

**Figure 4.** Micrograph of Chips Produced at \(V=79\text{m/min}\) \(f=0.4\text{mm/tooth}\) while Machining at Room Temperature and Thermally Enhanced Machining at 191°C
Although there are obvious dissimilarities shown in Figure 4 when chips produced during TAM developed a primary serration form. This was believed to be influenced by low preheat temperature of 191°C and high feed of \( f = 0.4\text{mm/tooth} \) that was used. Figure 5 shows build up edge (BUE) phenomenon that was observed to initiate after three minutes cutting time until the tool failure criterion was attained. The BUE was believed to be due to local weld developed as a result of poor thermal gradient which also govern strain hardenability and restrain conduction heat transferred within the bulk material.

![Build up edge](image)

**Figure 5.** A Built up Edge Developed on Formed Chips during End milling Type 316L Stainless Steel At Room Temperature Condition while Cutting Speed of \( V = 50\text{m/min} \) and Feed rate \( f = 0.4\text{mm/tooth} \) using Uncoated WC – Co Insert

The chips obtained during machining at room temperature were observed to have high thickness and hardness. It was observed that the chips thickness varied when the feedrate was purposely increased while the cutting speed was maintained fixed at 79m/min. Amin et al [7] attributed thinner chips to lower cutting forces and stresses expended on the cutting tool. The chips obtained during both conventional machining at room temperature and while thermally assisted machining shows that chips thickness was influenced by cutting speed and preheat temperature, and that, with increase of preheat temperature, the chips thickness increases with decreases of saw tooth shape. Rao [13] reported that some of the ideal conditions that promote continuous chips in metal cutting included small chip thickness and high cutting speeds. Figure 6. Show an evident influence of feed rate on chip thickness during TAM and conventional machining at room temperature condition using uncoated WC – Co insert on type 316L stainless steel. It is generally concluded from the scope of the parameters investigated in this study that while the vibration amplitude decreases during thermally assisted machining, the surface roughness of type 316L decreases. The chips formed during thermally assisted machining are less hard with faded saw tooth shape. This implies that the resulting cutting force and the stress expended on the cutting tool are minimum as compared to when machining at room temperature conditions. This phenomena was believed to play a significant role lowering the tool wear and machine chatter amplitude as well, as reported in Amin et al [7] and Masood et al [14]. Hence, decreased machine vibration during end milling type 316L stainless steel using uncoated WC-Co insert substantiates that machinability improvements can be attained using oxyacetylene gas flame as a heat source for thermally enhanced machining process. In conclusion, the chips that are obtained during TAM are continuous type that exists in the classes of washer type – helical chips and connected arc chips. However, both continuous and discontinuous chips were observed while machining at room temperature conditions. The chips type during this condition exists in the classes of arc chips (connected and loose) and snarled washer type – helical chips.
Figure 6. Influence of Feed Rate on Chip Thickness during Thermally Enhanced Machining and Conventional Machining at Room Temperature Condition using WC – Co Insert on Type 316L Stainless Steel (V = 79m/min)

5. Conclusions

From the scope of the study presented here, it is reliably concluded that the cutting parameters significantly influences the morphology of chips formed. This chips resulting from machining 316L stainless steel using WC-Co insert are characterized in form of saw tooth during TAM and conventional cutting at room temperature. However, chips formed during TAM are less hard with faded saw tooth shape. This implies that the resulting cutting force and the stress expended on the cutting tool are minimum as compared to when machining at room temperature conditions where the saw tooth shape is evidently characterized in form of both primary and secondary serration.

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