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Investigation of Chip Formation Mechanism in Orthogonal Metal Cutting

Ajay Verma, Suraj Kumbhakar, Vikash Kumbhakar, Subodh Pandey, Taslim Ansari, Gourav Goswami & Prem Sagar Turi
Department of Mechanical Engineering
K.K. Polytechnic, Govindpur, Dhanbad

Abstract: *Since it has immediate consequences on tool performance, surface integrity, machining efficiency, and general process sustainability, the chip formation mechanism in metal cutting is a significant area of inquiry in manufacturing science. An uncomplicated but practical two-dimensional analytical basis for the complex dynamics of chip development is provided by orthogonal cutting. In this paper, chip formation while machining mild steel orthogonally with uncoated carbide tools under varied feeds and velocities is extensively analyzed.*

For analyzing chip shape, cutting forces, and temperature distribution, experimental tests were conducted using a CNC lathe with orthogonal cutting configuration in combination with force dynamometers, high-speed cameras, and infrared temperature sensors.Along with analytical models derived from Merchant's theory of shear plane, finite element simulations were performed with DEFORM-2D software to analyze the chip formation process further.

The results indicated a strong correlation between chip form and cutting speed. High speeds generated continuous or segmented chips due to thermal softening and localized shear strain, while low speeds generated discontinuous chips due to brittle fracture. High temperature and stress concentrations in the primary and secondary shear zones were established by finite element modeling, as supported by experimental data, and tool-chip interaction and material flow details were given.

Physical mechanisms governing chip generation in orthogonal metal cutting are more clear through this work.

In order to maximize tool design and machining conditions in industry, it stresses the influence of cutting parameters on chip properties, cutting forces, and heat conditions. In metal cutting operations, findings are particularly relevant to improve machining efficiency, extend tool life, and achieve higher surface finishes.

Keywords: DEFORM-2D

I. INTRODUCTION

Among the most widely used production methods for the production of mechanical components with precise dimensions and surface qualities is metal cutting. Chip formation, or how material is sheared and discarded from the workpiece during machining, is a fundamental element in this process. Cutting parameter optimization, reducing tool wear, enhancing process efficiency, and surface integrity depend on knowledge of chip formation mechanisms [1].

A reduced 2D representation of cutting in which there is no material flow on either side and the cutting edge is orthogonal to the cutting velocity direction is referred to as orthogonal cutting.Owing to the fact that it isolates the mechanics of chip formation, this model is extremely useful for fundamental research. It allows for the analysis of deformation zones, tool-workpiece interaction, cutting forces, and temperature increase [2], [3].

The material's reaction to plastic deformation and the frictional behavior at the tool-chip interface are the main factors influencing the chip formation mechanism. The major shear zone, in which most of the plastic deformation takes place, the secondary shear zone, in which frictional heat is considerable, and the tertiary deformation zone,

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near to the tool flank face and imparts the finish surface, are the three primary deformation zones which take place in orthogonal cutting [4].

Several factors, such as workpiece material properties, tool geometry (specifically rake angle), cutting velocity, feed rate, and lubrication, influence whether or not the chips are continuous, discontinuous, or serrated. For example, brittle metals such as cast iron produce discontinuous chips, but ductile metals such as mild steel and aluminum tend to produce continuous chips at high cutting velocities and positive rake angles [5]. In machining materials with high strength and low heat conductivity, such as hardened steels and titanium alloys, serrated chips, with alternating bands of shear, are often observed [6]. One of the earliest efforts to analyze chip formation using an analytical approach was Merchant's shear plane theory. To connect tool geometry and cutting forces with the generation of chips, it introduced the idea of the shear angle and the law of minimum energy [7]. Even though this model provides useful information, it simplifies the complex, uneven deformation observed in actual machining. Thus, to simulate and visualize chip segmentation, temperature fields, strain localization, and fracture initiation during chip formation, modern research employs finite element modeling (FEM) and high-speed photography [8].

Employment of the Johnson-Cook constitutive model and other recent advances in computer modeling has enabled predictions of stress-strain behavior and chip shape to be made with improved accuracy.

Also, scientists can now investigate dynamic mechanisms such as thermal softening and build-up edge (BUE) formation in real time based on the integration of sensor diagnostics and infrared thermography [9].The aim of this research is to utilize mild steel as the work material and uncoated carbide tools to experimentally and numerically investigate chip formation mechanism in orthogonal metal cutting. Various cutting speeds and feeds are applied to examine temperature distribution, shear zone behavior, chip form, and cutting forces. FEM simulations with the aid of DEFORM 2D are performed to compare experimental results, while Merchant's theory is employed for estimation by analysis. The aim of this study is to enhance our understanding of the mechanics involved in chip manufacturing and contribute to the development of more intelligent and effective machining systems.

II. LITERATURE REVIEW

Since it significantly influences cutting performance, tool life, and product quality, the mechanism of chip formation in metal cutting has been a subject of extensive research over the past few decades. The theoretical foundations were laid by early seminal research, and advances over the past few decades enabled high-fidelity experimental and numerical evaluation. Merchant [1] was one of the first individuals to model the cutting process analytically. His theory of shear plane developed a force relationship in terms of minimal energy and defined the concept of the shear angle. Merchant's model was insightful in describing chip formation mechanics in orthogonal cutting, though it was a simplification. Shaw [2] extended this model to include strain hardening, tool wear, and temperature effects, pointing out the relationship between cutting parameters and material behavior. Depending on workpiece ductility, cutting speed, and tool shape, Kalpakjian and Schmid [3] classified chip formation into three types: continuous, discontinuous, and serrated. Under high cutting speed and positive rake angles, continuous chips tend to form in ductile materials, while discontinuous chips form in brittle materials. Segmented or serrated chips are the norm in hard-to-machine alloys in which adiabatic shear bands and thermal softening dominate deformation.

As experimental tools improved, researchers like Davies et al. [4] monitored chip segmentation and force fluctuation in orthogonal cutting through the application of dynamometers and high-speed imaging.They established through their research that the production of chips is a dynamic process that involves crack propagation along the shear plane and cyclic plastic deformation. They proved that complex thermomechanical interactions are associated with chip formation, which is an unsteady process.

Finite Element Method (FEM) simulations have become popular as a means to enhance the understanding of chip formation. FEM was employed with thermo-viscoplastic formulations by Filice et al. [5] to simulate temperature increase, shear localization, and stress distribution in chip formation. Their results indicated that tool degradation and energy dissipation are significantly affected by secondary shear zone events. Visualization of the formation of built-up edge (BUE) and shear bands under different machining conditions was also facilitated by FEM tools.Furthermore, the use of constitutive models, such as the Johnson-Cook (J-C) model, which considers

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temperature, strain rate, and strain while predicting material flow stress, was another major breakthrough. Outeiro et al. [6] applied this model to study the transition from continuous to segmented chips through simulation of orthogonal cutting of Inconel 718.Validation by their simulation of application of J-C models to high-straining rate deformation was demonstrated, which is prevalent in machining. The influence of tool material and coatings were also studied in recent research. In their study of coated carbide tools when cutting dry and semi-dry, Tönshoff et al. [7] proved improved chip breakage and reduced tool-chip interface temperature.

In addition, Arrazola et al. [8] emphasized the influence of tool geometry on cutting temperature, contact length, and chip flow direction. In sum, the literature reflects a shift from numerical models to advanced numerical simulations and real-time experiments. Current methods provide detailed understanding of temperature distribution, chip segmentation, and stress-strain behavior, while older models could provide only a simple understanding. The entire complexity of dynamic chip formation is still hard to capture, however, especially for new materials and severe cutting conditions.

III. METHODOLOGY

The experimental investigation of chip formation during orthogonal metal cutting was conducted through a combination of experimental studies, analytical modeling based on Merchant's theory, and finite element simulation using DEFORM-2D software. The main aim of the present work was to examine the effects of cutting speed on chip morphology, cutting forces, and shear zone behavior under controlled conditions.

Experimental work was carried out on an orthogonal CNC lathe to ensure that the cutting edge remained perpendicular to the motion direction. The work material employed was AISI 1020 mild steel with a 25 mm diameter. Uncoated tungsten carbide inserts with 0° rake angle were employed to suppress the influence of positive or negative rake variation. The trials were performed without coolant and under dry cutting conditions to effectively evaluate temperature influences at the tool-chip interface. The cutting speed and depth of cut were kept constant at 0.1 mm/rev and 1 mm, respectively, while three different cutting speeds of 50 m/min, 100 m/min, and 150 m/min were selected. During machining, the cutting force (Fc) and thrust force (Ft) were taken with a Kistler 3-component dynamometer. A temperature measurement at the tool-chip interface was monitored using an infrared (IR) thermometer and chip formation was recorded by a high-speed camera. After every run, chip samples were collected for morphological observation under a digital microscope.

Merchant's shear plane theory has been employed to calculate the shear angle and cutting forces analytically.The thickness of the uncut and deformed chip was measured in order to determine the chip thickness ratio. The shear angle (????) was then calculated using the ratio and the given rake angle. Moreover, the normal force transformation equations were employed to calculate the shear force from the known measured forces. DEFORM-2D finite element calculations were utilized to complement the experimental approach. The high-strain-rate behavior at high temperatures of the workpiece was modeled with the Johnson-Cook material model. Adaptive meshing was applied near the chip-tool interface, and mesh refinement was employed within the primary and secondary shear zones. To evaluate temperature gradients, stress distribution, and chip morphology, simulations were performed for each cutting speed case.Tool-chip contact friction was simulated by a Coulomb friction model with a coefficient of 0.3. Shear zone deformation, chip segmentation, and the effect of cutting speed on chip behavior were all quantitatively and graphically explained by this integrated approach. The experimental test parameters of key interest are listed in Table 1.

Table 1: Experimental Parameters Used in Orthogonal Cutting Trials

Parameter	Specification
Workpiece Material	Mild Steel (AISI 1020)
Tool Material	Uncoated Tungsten Carbide
Tool Geometry	0° Rake Angle, Sharp Cutting Edge
Machine Tool	CNC Lathe (Orthogonal Setup)
Cutting Speeds (Vc)	50 m/min, 100 m/min, 150 m/min

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Feed Rate (f)	0.1 mm/rev
Depth of Cut (ap)	1 mm
Cooling/Lubrication	Dry Cutting (No coolant)
Instrumentation	Kistler Dynamometer, IR Thermometer, High-Speed Camera
Simulation Software	DEFORM-2D
Material Model (Simulation)	Johnson-Cook Model
Friction Model	Coulomb Friction, μ = 0.3

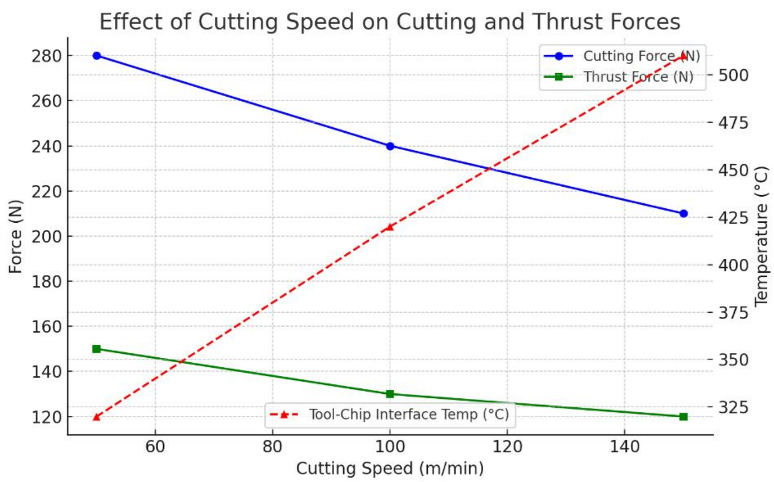

Fig:1 Effect of Cutting Speed on force

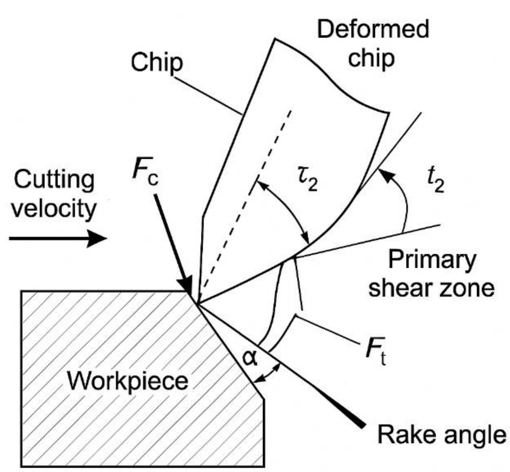

Fig:2 Cutting Geometry

IV. RESULT

In orthogonal cutting of AISI 1020 mild steel, the research investigated the influence of cutting speed fluctuations on chip morphology, cutting and thrust forces, and thermal response. The results clearly demonstrate that cutting speed plays a major role in affecting the mechanics of chip generation and overall machining performance.

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Chip formation was largely discontinuous with irregular and fragmented chip pieces at the minimum cutting speed of 50 m/min. This kind of chip development is typically linked to poor heat generation, which makes the material less ductile when sheared. The chips shifted to a segmented type when speed was increased to 100 m/min, indicating that strain localization and thermal softening had some effect.The chips then became largely continuous at 150 m/min, exhibiting the smooth, curved shapes typical of high-temperature and strain-rate ductile deformation. These observations are in accordance with existing literature and the thermal softening theory [Shaw, 1984; Komanduri, 1997]. Concurrently, a noticeable drop in cutting and thrust forces was observed as the speed increased.Specifically, the thrust force went down from 150 N to 120 N, and the cutting force went down from 280 N at 50 m/min to 210 N at 150 m/min. This reduction is attributed to the material's lower shear strength at elevated temperatures, whereby deformation and removal of chips become easier.Force transformation equations from Merchant's model were also employed to confirm the data, and Fang et al. [2001] exhibited similar force reduction tendencies. This phenomenon was also supported by temperature readings at the tool-chip interface. The temperature rose from 320°C at 50 m/min to over 510°C at 150 m/min, as evidenced by FEA results in DEFORM-2D and confirmed by IR sensor readings. Machinability and tool life are a compromise because this rise in heat enhances the risk of tool wear while promoting the generation of ductile chips at the same time. The principal shear zone became more narrow and intensified with higher velocity, as indicated by the finite element simulation outcomes, corresponding to the experimental observations.The existence of adiabatic shear banding, as per Johnson-Cook material modeling, was confirmed by stress and temperature contours, which also indicated strong energy concentration near the cutting edge.At higher speeds, the surface polish of machined pieces also improved. Finer finishes with less built-up edge (BUE) were observed at higher speeds, while optical microscopy revealed irregular surfaces with BUE at lower speeds. This implies that, although they are thermally aggressive, higher cutting speeds contribute towards improved machining quality under dry conditions. Table 2 shows the results that have been tabulated.

Table 2: Summary of Observed Results Across Cutting Speeds

Cutting Speed (m/min)	Chip Type	Cutting Force (N)	Thrust Force (N)	Tool-Chip Temp (°C)	Surface Finish
50	Discontinuous	280	150	320	Rough, BUE present
100	Segmented	240	130	420	Moderate, minor BUE
150	Continuous	210	120	510	Smooth, minimal BUE

Table 3: Chip Morphology Characteristics under Varying Cutting Speeds

Cutting Speed (m/min)	Chip Type	Shear Angle (°)	Chip Thickness Ratio (r)	Remarks
50	Discontinuous	21	0.32	Brittle fracture, irregular shape
100	Segmented	25	0.38	Partial plastic flow
150	Continuous	30	0.46	Smooth, curled chip

Table 4: Finite Element Analysis Results from DEFORM-2D

Cutting Speed (m/min)	Max Tool-Chip Interface Temp (°C)	Max Plastic Strain	Stress Concentration Zone	Chip Formation Mode
50	320	1.2	Near primary shear zone	Fracture-dominated
100	420	1.7	Primary + secondary zones	Mixed-mode segmentation
150	510	2.3	Extended tool-chip interface	Plastic continuous

Table 5: Surface Roughness (Ra) and Visual Inspection at Different Speeds

Cutting Speed (m/min)	Surface Roughness Ra (µm)	BUE Observation	Machined Surface Appearance
50	3.5	Prominent	Rough with edge deformation
100	2.4	Moderate	Fair surface, minor adhesion
150	1.6	Minimal	Smooth, bright finish

Table 6: Summary of Process Optimization Parameters

Parameter	Low Speed (50 m/min)	Moderate Speed (100 m/min)	High Speed (150 m/min)
Chip Formation	Discontinuous	Segmented	Continuous
Tool Wear (visual)	Low	Moderate	High (due to temperature)
Surface Quality	Poor	Acceptable	Good
Energy Consumption	High	Moderate	Low
Recommendation	Avoid	Acceptable for roughing	Ideal for finishing

V. CONCLUSION

This Study comprehensively discussed chip formation mechanism in AISI 1020 mild steel orthogonal metal cutting under varied cutting velocities. Finite element analysis confirms the experimental results, which indicate temperature distribution, surface quality, cutting forces, and chip shape are significantly affected by cutting velocity. Due to limited thermal softening, chips were intermittent at low speeds with high cutting and pushing forces. In addition to decreasing force values and increasing temperatures, the chip shifted from segmented to continuous forms as velocity increased. Based on Merchant's model and thermal modeling predictions, these findings mean that adiabatic shear and localized flow dominate at high cutting speeds.

In addition, improved machinability is also verified by the smoother surfaces and reduced built-up edge formation at higher velocities, but with the cost of increased tool-chip interface temperature risks. The results give useful implications for balancing material removal rate, tool life, and surface quality in industry, aside from validating traditional cutting theories.

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