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INFLUENCE OF CUTTING SPEED ON CHIP MORPHOLOGY IN TURNING

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Abstract: This paper investigates, through a systematic experimental approach, the influence of cutting speed on chip morphology in the dry machining of AISI 5140 steel using carbide insert tools. The experimental results revealed a gradual transition in chip morphology, from fragmented and irregular chips at low cutting speeds to continuous chips at the highest cutting speed tested. Furthermore, the chip compression ratio decreased as cutting speed increased, indicating a reduction in plastic deformation, whereas the chip thinning ratio increased, reflecting a more uniform material flow. It was also observed that the increase in cutting speed favoured the transition from segmented to continuous chip formation under conditions of elevated temperature in the tool–chip contact zone. Overall, the results confirm the essential role of cutting speed in controlling chip formation during the dry machining of hardened steels.
Keywords: speed, temperature, thickness, fragmentation, chip

1. INTRODUCTION

Turning is one of the most widely employed machining operations in modern manufacturing due to its versatility, efficiency, and ability to produce components with high dimensional accuracy. Within this process, chip formation and fragmentation mechanisms are of fundamental importance for understanding the interaction among the cutting tool, the workpiece material, and the machining conditions [1]. As modern industry increasingly seeks to enhance productivity while reducing manufacturing costs, chip morphology control has become a strategic element in machining process optimization [2]. The chip should not be regarded as a secondary product of the cutting process; rather, it reflects the plastic deformation mode of the material, the temperature developed in the cutting zone, the cutting forces, and the wear state of the cutting tool, while directly affecting process stability and efficiency, as well as the quality of the machined surface [3].

The scientific study of chip formation began to develop rigorously during the 1930s and 1940s, building on Taylor's investigations into the relationship between cutting parameters and tool behaviour, as well as on Mallock's experimental work concerning deformation mechanisms and the shearing process in the cutting zone [4].

Among the cutting parameters, cutting speed exerts the most pronounced effect on the thermomechanical phenomena taking place in the cutting zone, which ultimately govern chip morphology. One of the major consequences of cutting speed variation is the modification of the chip formation mechanism [5].

The literature also indicates clear transitions between machining regimes characterized by segmented chips at low cutting speeds and those characterized by continuous chips at higher cutting speeds [6]. Therefore, cutting speed should not be considered merely a numerical parameter used to define the cutting regime, but rather a determining factor for the stability, controllability, and overall performance of the entire machining process [7].

The sensitivity of chip morphology to cutting speed variation provides the rationale for the present study, which examines the relationship between cutting speed and the type of chip generated during the turning of AISI 5140 steel under different cutting speed conditions. Most currently available studies focus either on the theoretical modelling of chips produced in various machining processes or on large–scale experimental analyses performed using high–capacity machine tools and high–performance cutting tools capable of ensuring highly controlled cutting conditions. By contrast, fewer studies have addressed the influence of cutting speed on chip morphology under light–machining conditions and at moderate cutting speeds. Furthermore, a significant part of the existing literature does not directly correlate cutting speed with its specific morphological effects in AISI 5140 steel, but rather presents generalized findings for the broader class of chromium–alloy steels.

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Accordingly, the present paper is positioned within a relatively insufficiently explored area of research and aims to establish a simultaneous correlation among chip morphology, chip compression ratio, and temperature in the workpiece-tool-chip system during the dry turning of AISI 5140 steel at moderate cutting speeds. The experimental investigation was carried out under controlled laboratory conditions, using machining parameters representative of educational applications and small—scale precision operations.

The main contribution of this study lies in the direct correlation established between cutting speed, chip morphology, chip compression ratio, and the thermal conditions in the workpiece-tool-chip system during the dry turning of AISI 5140 steel under moderate cutting speed conditions.

2. PROBLEM DESCRIPTION

The chip formation mechanism is similar for most machining processes and is described by the occurrence and evolution of three deformation zones: primary, secondary, and tertiary [8]. In the primary zone, shear stresses develop and the material structure becomes severely distorted. The deformed material then comes into contact with the rake face of the cutting tool, where it undergoes further plastic deformation within the secondary deformation zone, after which it is released into the space above the tool in the form of chips [9]. Figure 1 illustrates the chip formation model in longitudinal turning.

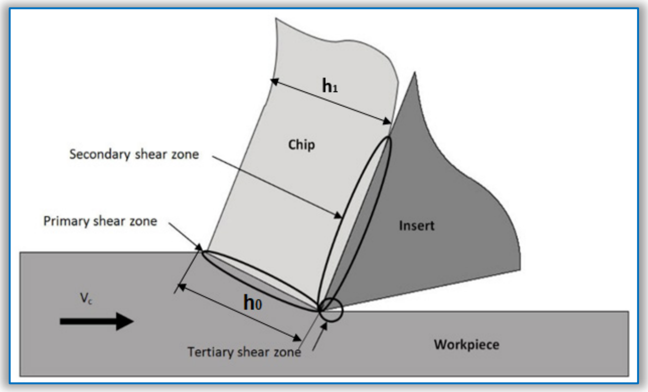


Figure 1. Chip formation model in turning

In the analysis of chip formation mechanisms, an important synthetic parameter is the chip compression ratio, defined as the ratio between the thickness of the formed chip (h_1) and the thickness of the undeformed chip thickness (h_0) [10]:

$$r_c = \frac{h_1}{h_0} \quad (1)$$

This indicator is directly associated with the intensity of plastic deformation in the primary shear zone and with the tribological conditions at the tool-chip interface. As a complementary parameter, the chip thinning ratio (r_t), defined as the inverse of the chip compression ratio, can be used for comparative interpretation [11]:

$$r_t = \frac{h_0}{h_1} = \frac{1}{r_c} \quad (2)$$

The variation of these two parameters as a function of cutting speed allows a more accurate characterization of the chip formation phenomenon and of the influence of cutting speed on the machining process [5].

Undeformed chip thickness (h0) can be determined on the basis of the actual geometric model of the cutting process, which is established from the relationship between tool feed and the principal cutting edge angle. Based on this model, the thickness of the undeformed chip thickness is determined by the following relation [12]:

$$h_0 = f \cdot \sin \kappa_r \quad (3)$$

where: f is the feed per revolution, in mm/rev, and κr is the principal cutting edge angle of the cutting tool, expressed in degrees.

The thickness of the formed chip (h_1) is determined experimentally by direct measurement of chip fragments, which makes it possible to quantify the changes induced by the cutting parameters on chip morphology and on the deformation regime [10].

During the cutting process, a considerable amount of heat is generated, leading to a temperature rise in the cutting zone, namely in the workpiece-tool-chip system. The heat produced in this region results from the deformation of the workpiece material up to plastic flow in the primary deformation zone A-B. Owing to this deformation process, the largest proportion of heat is generated in the secondary shear zone B-C, while the remaining part is produced by friction between the cutting tool and the workpiece in the tertiary shear zone B-D, Figure 2 [11].

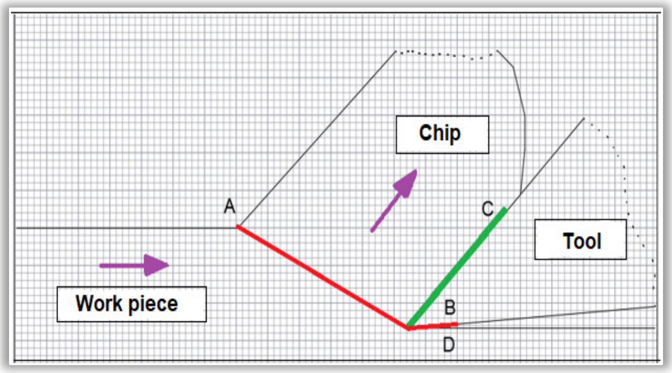


Figure 2. Heat transfer in the cutting process

The non—uniform heat distribution across the three deformation zones significantly affects chip formation mechanisms, process stability, and cutting tool wear, thereby representing an essential factor in the analysis of the cutting process [8], [10].

3. EXPERIMENTAL PROCEDURE

The experiments were carried out on an SNB 400 × 2000 mm lathe under dry cutting conditions during the longitudinal semi—finishing turning of hardened AISI 5140 steel (≈60 HRC). For each experiment, a cylindrical workpiece with a diameter of 50 mm was machined over a length of 100 mm, using a single pass. Machining was performed with a carbide insert cutting tool, grade H13A, equipped with a DNMG 1506 insert and mounted on a rigid DDJNR 2525M15 tool holder, having a principal cutting edge angle of κr = 93°. To ensure comparability among the experiments, a new insert was used for each test, while maintaining the same initial geometric characteristics of the cutting edge. The experimental plan kept feed rate and depth of cut constant, whereas cutting speed was varied by changing the spindle speed of the machine tool, according to the parameters presented in Table 1. In this table, the cutting speed was calculated using the following relation:

$$v = \frac{\pi \cdot d \cdot n}{1000} \tag{4}$$

where: d - workpiece diameter, [mm] and n - spindle speed, [rev/min]

Tabelul 1. Cutting mode parameters

NO. CRT.	SPINDLE SPEED n [rot/min]	CUTTING SPEED v [m/min]	DEPTH OF CUT a_p [mm]	FEED f [mm/rot]
Experiment 1	125	19,6	0,5	0,1
Experiment 2	250	39,3		
Experiment 3	500	78,5		

Figure 3 shows a sequence from the experiments, and Figure 4 shows the piece positioned in the universal lathe at the end of experiment 1.

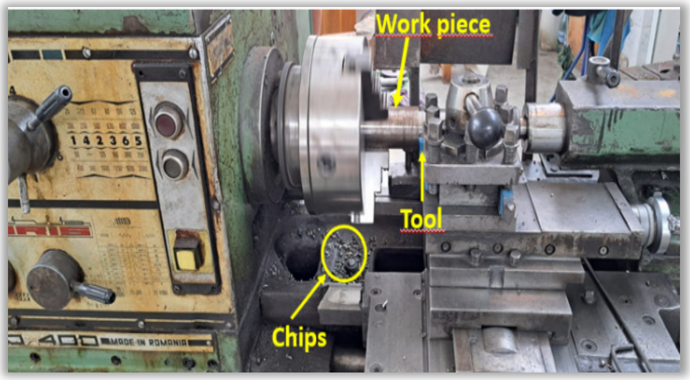


Figure 3. Machining sequence during the experiments

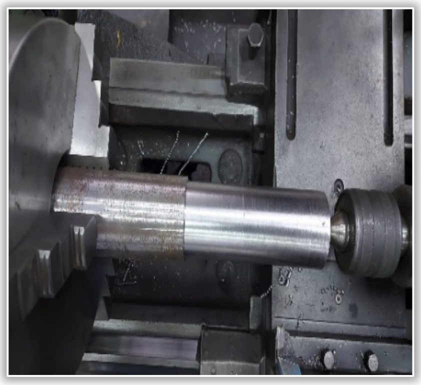


Figure 4. Workpiece at the end of Experiment 1

After each experiment, the resulting chips were collected for subsequent analysis. Their visualization and characterization were performed using an A—KRUSS OPTRONIC optical microscope, which allows the acquisition of digital images of the chips produced during the machining process.

The thickness of the formed chip (h_1) was determined experimentally by direct measurement of the chip fragments collected for each cutting regime Figure 5. In order to ensure the representativeness of the results and to limit the influence of local variations (curvature, waviness, and segmentation), ten chip fragments were selected, and for each fragment the measurement was carried out in comparable areas, avoiding the edges and the portions accidentally deformed. For each experiment, n=10 measurements were performed, and the value used in the calculations was the arithmetic mean, determined using the following relation:

$$\overline{h}_1 = \frac{1}{n}\sum_{i=1}^{10} h_{1,i} \tag{5}$$

Figure 6 presents the chips obtained at the end of Experiment 1, prepared for thickness measurement. Based on the values of $\overline{h}_1$ și h0, the chip compression ratio (rc) and the chip thinning ratio (rt) were calculated for each cutting regime.

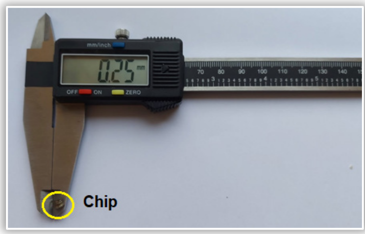


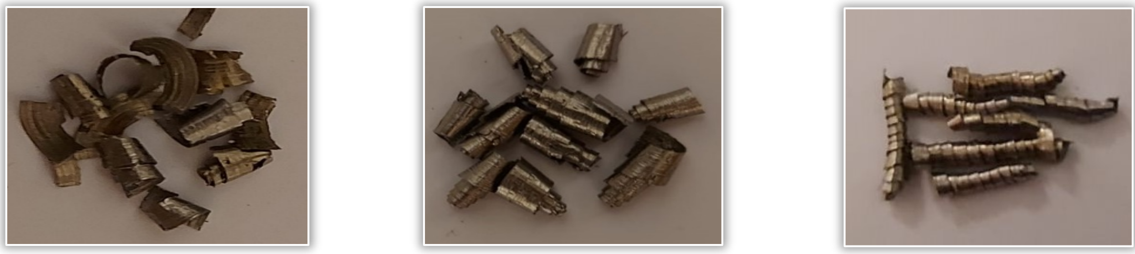
Figure 5. Measurement of the thickness of the chips obtained

Figure 6. Measurements carried out for the determination of chip thickness in Experiment 1

During the experiments, the temperature in the cutting zone (workpiece-tool-chip) was monitored using an infrared thermal imaging camera, which allows non—contact measurements with an accuracy of ±2°C.

4. RESULTS AND DISCUSSION

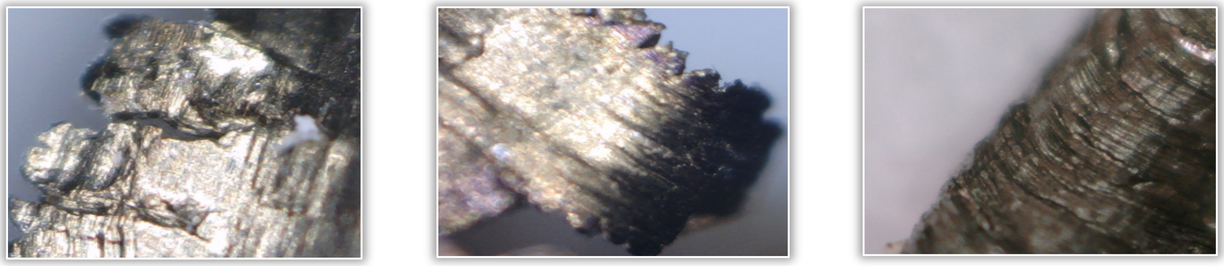
The chips obtained in the three experiments exhibited different shapes, sizes, and colors, as illustrated in Figure 7.



EXPERIMENT 1 EXPERIMENT 2 EXPERIMENT 3

Figure 7. Chips obtained at the end of the experiments

Figure 8 shows the chips obtained during machining, as visualized with an optical microscope equipped with a digital interface. The images allow the analysis of chip morphology and fragmentation type, as presented in Table 2.



EXPERIMENT 1 EXPERIMENT 2 EXPERIMENT 3

Figure 8. Optical microscope images of the chips obtained, acquired using the A—KRUSS OPTRONIC system

Table 2. Morphology of the chips resulting from the experiments

ANALYSED CHARACTERISTIC	EXPERIMENT 1	EXPERIMENT 2	EXPERIMENT 3
APPEARANCE	Short, segmented, thick, serrated	Helical, short, partially serrated, with rough areas	Helical, long, continuous, slightly glossy
STRUCTURE	Dense, compact	Slightly plastic zones appear between segments	More uniform plastic deformation
CRACKS	Cracks inside each segment	Cracks on the chip surface	Short cracks on the chip surface
COLOUR	Light gray	Light gray to light brown	Ash gray to reddish—brown
ELASTICITY	Low elasticity; the chips break immediately	Moderate elasticity; the chips deform slightly before breaking	High elasticity; ductile and continuous chip

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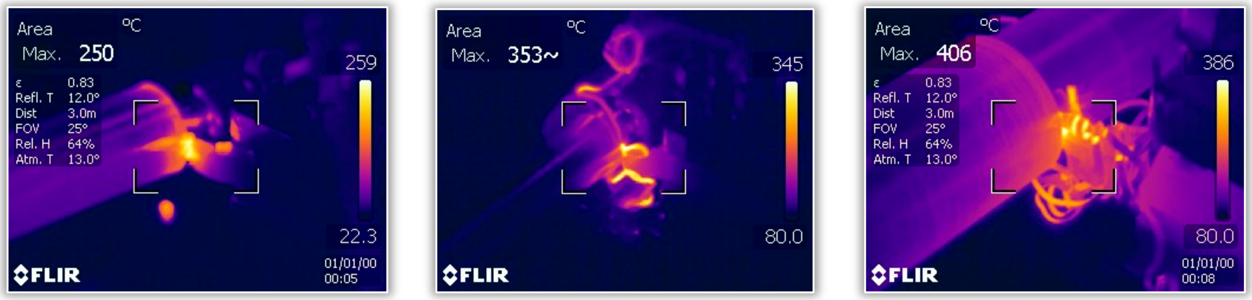
At low cutting speeds (Experiment 1), the chips are short, segmented, and coarse in structure, and they break periodically, indicating low elasticity and cohesion. As a result of the high hardness of the material, the cutting process is brittle, which promotes chip breakage.
At medium cutting speeds (Experiment 2), the chips become semi–continuous and partially fragmented, exhibiting moderate elasticity and slight deformation before breaking, which indicates an increase in local plastic deformation.
At high cutting speeds (Experiment 3), the chips show a continuous and locally ductile behaviour, highlighting increased elasticity and cohesion. The obtained results reveal a transition from short, fragmented chips to long, continuous chips, which is a sign of a more stable cutting process. The observed behaviour is consistent with the known chip formation mechanisms for hard materials reported in the specialized literature [11]. These results confirm the direct correlation between cutting speed, material deformation, and the morphology of the resulting chip.
In addition to the morphology of the chips obtained at the end of the experiments, the local temperature in the cutting zone was also determined, Figure 9.



EXPERIMENT 1 EXPERIMENT 2 EXPERIMENT 3

Figure 9. Cutting zone temperature at the end of each experiment

Figure 9 shows that, at low cutting speeds, the temperature at the end of the experiment was approximately 250°C, while the chips were short, serrated, and light gray in colour. At medium cutting speeds, the temperature increased to above 350°C, corresponding to the appearance of semi–continuous chips with moderate elasticity and a colour ranging from light gray to light brown.
At high cutting speeds, the temperature exceeded 400°C, favouring the formation of continuous, ductile chips with a colour varying from ash gray to reddish–brown. The increase in cutting speed promotes a rise in temperature within the shear zone, a reduction in the effective shear stresses, and an easier deformation of the material, which leads to the formation of thinner and more continuous chips [13].
In order to evaluate the influence of cutting speed on chip formation and fragmentation mechanisms, the chip compression ratio, as well as the chip thinning ratio, were determined, and the results are presented in Table 3.

Table 3. Determination of the chip thickness ratio parameters

NO. CRT.	UNDEFORMED CHIP THICKNESS h_0 [mm]	AVERAGE THICKNESS OF THE RESULTING CHIP h_1 [mm]	CHIP COMPRESSION RATIO r_c	CHIP THINNING RATIO r_t
EXPERIMENT 1		0,21	2,103	0,4755
EXPERIMENT 2	0,09986	0,15	1,502	0,6657
EXPERIMENT 3		0,11	1,102	0,9078

Table 3 shows that, at low cutting speeds (Experiment 1), the chip compression ratio is high, which indicates severe plastic deformation and the formation of chips under significant compression. As the cutting speed increases (Experiments 2 and 3), this ratio decreases, indicating improved cutting efficiency and the formation of thinner, more elongated, and more continuous chips.
Figure 10 illustrates the variation of the chip compression ratio as a function of cutting speed. An inverse relationship can be observed, with the values of the chip compression ratio decreasing as cutting speed increases, which indicates reduced plastic deformation in the shear zone and a more uniform material flow during the cutting process.
The behaviour highlighted above is characteristic of the machining of hard materials such as hardened AISI 5140 steel, where higher cutting speeds lead to reduced plastic deformation of the

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material prior to separation, thus generating thinner chips relative to the theoretical thickness. This behaviour has also been reported in the specialized literature [6], [13], [14]. These findings support the observations regarding reduced plastic deformation and the formation of thinner chips at high cutting speeds.

With regard to the chip thinning ratio, a significant increase can be observed as cutting speed increases, indicating a reduction in plastic deformation in the shear zone and a more uniform material flow as a result of the temperature rise and the decrease in the shear strength of the machined material. This phenomenon is associated with a change in the chip formation regime, namely a transition from a regime characterized by thick and compressed chips to one involving thinner and more elongated chips, which are typical of high cutting speeds. This observation is also confirmed by the studies reported in [12], [13].

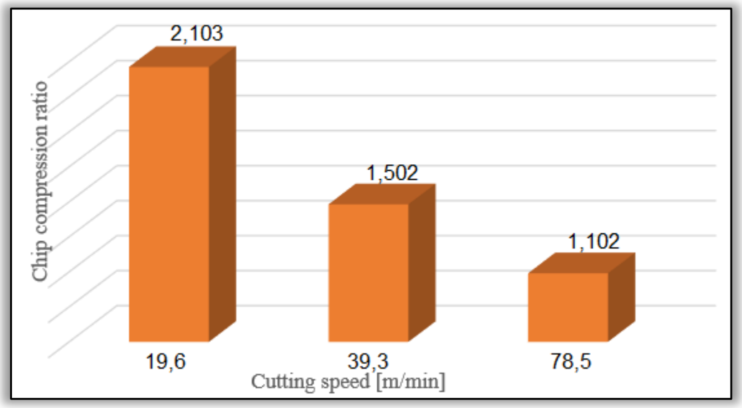

Figure 10. Variation in the chip compression ratio as a function of cutting speed

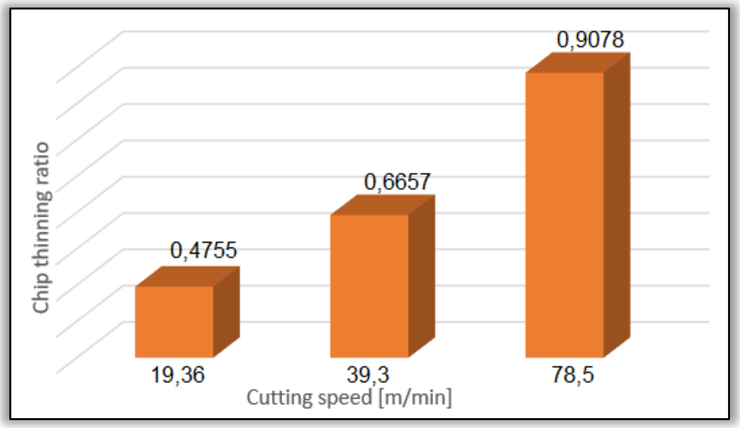

Figure 11. Variation in the chip thinning ratio as a function of cutting speed

By correlating the visual observations of the resulting chips with the thermal regime, it can be noted that the intensification of chip colour, from metallic tones to reddish–brown shades at high cutting speeds, indicates the progressive increase in temperature in the cutting zone, thus confirming the change in material behaviour from brittle to ductile as cutting speed increases.

The experimental results highlight that cutting speed directly influences chip morphology, the chip compression ratio, and the temperature in the cutting zone.

From a technological point of view, the obtained results confirm the importance of selecting an optimal cutting speed in order to ensure an efficient and stable machining regime in the turning of hardened steels under dry cutting conditions.

6. CONCLUSIONS

The conclusions drawn from this study are applicable to both light industrial machining and educational activities or workshop operations. They may be summarized as follows:

- Cutting speed significantly influences chip formation and fragmentation mechanisms, leading to changes in chip morphology, as well as in the chip thickness ratio parameters;
- The increase in cutting speed led to a progressive decrease in the chip compression ratio, which suggests a reduction in the intensity of plastic deformation and a more uniform chip flow;
- The chip thinning ratio increased with cutting speed, confirming the transition toward thinner and more elongated chips at high cutting speeds.
- The temperature in the cutting zone increased with cutting speed (≈250°C to >400°C), modifying the thermomechanical regime and being associated with visible changes in chip colour and apparent ductility;
- In the present study, the medium cutting speed may be considered the most balanced condition, simultaneously providing process stability, cutting efficiency, and adequate thermal control.

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