REVIEW ARTICLE

Dynamics of chip formation during the cutting process using imaging techniques: A review

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Abstract
Imaging techniques have been widely implemented to study the dynamics of chip formation. They can offer a direct method and a full field measurement of the cutting process, providing kinematic information of the chip formation process. In this article, the state of the art of the imaging techniques reported in the literature has been summarized and analyzed. The imaging techniques have been applied to study the chip formation mechanism, friction behavior, strain/strain rate, and stress fields. Furthermore, the study of surface integrity has been advanced by deriving the thermo-mechanical loading, subsurface deformation, and material constitutive model from the imaging technique. Finally, achievements in the area of imaging techniques have been summarized, followed by future directions for their application in the study of surface integrity.

KEYWORDS
chip formation, imaging techniques, strain rate, stress, surface integrity

1 | INTRODUCTION

Machining is still the most common manufacturing operation nowadays, so it is of great value to study and model the machining process to improve productivity and product quality, and reduce the cost. These efforts on simulation of metal cutting mainly include analytical,¹,² numerical-based, and hybrid models,³ coupled with an innovative experimental technique⁴ to yield data for model development and validation. To this end, extensive research has been conducted to improve the cutting accuracy by means of advanced experimental techniques, such as in situ imaging and the microgrids method. The in situ information during machining can be obtained to validate and optimize the models, which can predict not only important variables (forces, temperature, chip geometry, etc.) but also industrial machining outcomes (surface integrity, tool wear, etc.).

Because of a closed-form solution and computationally efficient procedures, analytical models were more common in the early years.¹,²,⁵,⁶ Different analytical models are still being developed and used for different cutting conditions, including tools with different designs (grooved,⁷,⁸ rounded edge,⁹-¹¹ and chamfered¹²-¹⁵), different microcutting processes,¹⁶ and for simulating serrated chip formation.¹⁷ Nevertheless, these models suffer from oversimplifications, and are not suitable for accurately capturing the complexity of the cutting process. Such process complexity is attributed to thermomechanical coupling, tool–chip contact conditions, material failure, metallurgical alteration, and so on.

Improvements in computer techniques allowed the study of the metal cutting process using numerical-based models. Because it can account for the effects of plasticity,¹⁸,¹⁹ damage,²⁰,²¹ contact,²² and microstructure evolution,²³ numerical simulation is becoming...
a powerful and comprehensive tool to study the metal cutting process. Its vast applications have been reported in previous publications. However, accurate determination of complex factors and validation of these numerical-based models on a global scale remain limited.6

To reduce the gap between modeling and the real cutting process, several experimental techniques have been used. Early efforts can be traced back to the microgrids method. Elaborated microgrids are inscribed on the side of the workpiece using different techniques, and then the deformation can be determined according to the distorted grid after machining. Combined with quick-stop devices, Stevenson and Oxley measured the strain rate field within the primary shear zone.27 Roth and Oxley constructed the slip-line field based on the experimentally measured flow field.28 Despite the success achieved by the quick-stop device, its main drawback is the nonnegligible time required to separate the tool from the workpiece, especially in high-speed cutting, causing the deformation state to be disrupted.

Therefore, the microgrids method is modified by using imaging techniques instead of a quick-stop device to freeze the cutting process. Recording the deformation of the grid as a series of images captured by high-speed cameras, the in situ information can be obtained by further postprocessing. Childs used the double-exposure technique to deduce the velocity, strain rate, and even slip-line field in the chip formation zone; the cutting speed was limited to 254 μm/min.29 Due to the development of high-intensity lighting systems and high-speed filming devices, Pujana et al.30 were able to measure the strain and strain rates in the cutting process when the speed reached 300 m/min. Sela et al.31 proposed a novel methodology for measuring the strain and strain rate fields in the primary shear zone using only a single image. Recently, two image correlation techniques called digital image correlation (DIC) and particle image velocimetry (PIV) have been developed. Similar to the microgrids method, a high-speed camera or a double-shutter camera is used to observe the material’s deformation. Moreover, the DIC technique does not require use of complex grids on the lateral surface of the workpiece.

This article focuses on the imaging technique (PIV or DIC) coupled with the microgrids method, and it is organized as follows. Section 2 presents a brief introduction of the devices and the principle of the imaging technique. Section 3 reviews the state of the art of the application of imaging techniques in the chip formation process. Section 4 describes the role of imaging techniques in surface integrity research. Finally, the advantages of imaging techniques in cutting processes and future research directions are discussed.

# IMAGING TECHNIQUE

Recent interest in a new method based on high-speed/high-resolution imaging techniques has created new opportunities to investigate not only the dynamics of chip formation but also distributions of strain and strain rates generated in the plastic deformation zones. The imaging technique is a process of visually capturing information with adequate exposure time and frame rate by means of imaging devices. In this section, imaging systems and digital image processing techniques are discussed.

## 2.1 Imaging systems

### 2.1.1 Digital high-speed camera types and lighting sources

The in situ imaging system mainly consists of an ultra high-speed camera and an ultra high-speed/high-resolution light source. Cameras can be categorized from low to high frame rates as follows: (a) high speed, with 50–500 frames per second (fps); (b) very high speed, with 500–100 000 fps; (c) ultrahigh speed, with 100 000–10 million fps (Mfps); and (d) super high-speed, in excess of 100 million fps. On the other hand, modern imaging technology has created two advanced modes: digital with the invention of the charge-coupled device (CCD) and complementary metal–oxide–semiconductor (CMOS) detectors. CCD architecture captures higher-quality images, while CMOS enables superior integration and responsivity.33 A survey of high-speed cameras based on frame rate and CCD and CMOS technologies is presented in Figure 1, which shows that a CMOS-based higher frame rate camera sacrifices the resolution, while for CCD-based cameras, the resolution and frame rate are independent.

Light sources are another important factor of the imaging system. Short exposure time requires sufficient light to ensure high-quality pictures. Two categories of light sources are available for the imaging system: (a) continuous light source and (b) pulsed light source. Various types of lightings are summarized in Table 1. The two most popular lighting sources are laser and light-emitting diodes (LEDs). They both belong to “cold light” and do not generate high temperatures, which could affect the image quality.34 Moreover, the pulsed laser and LEDs offer the possibility to considerably reduce the interframe time.18,36

There exist two main methods to record images. One is using continuous light sources, and the exposure time is controlled by the camera shutter.37,38 The other is with the shutter open, and a synchronized pulsed light allows determination of the exposure time.18,36 It is worth noting that the latter system needs to be used in a dark room during the imaging period to reduce the noise.

### 2.1.2 Advanced in situ imaging systems

To understand local phenomena during chip formation, several experimental setups using imaging systems had been developed. An interesting study on kinematic field measurements was performed by Baizeau et al.39 They used a double-frame imaging device with pulsed lasers to obtain highly resolved images during orthogonal cutting and used a ×10 lens with a resolution of 0.66 μm/pixel. As shown in Figure 2A, a LaVision Imager sCMOS double-frame camera and a dual-pulsed laser were used to capture the images. This equipment captured image pairs before, during, and after the cutting at a frequency of 15 Hz using the synchronization system shown in Figure 2B.
Another well-organized imaging device for orthogonal cutting analysis was developed by Meurer et al. They conducted the experiments on a vertical external broaching machine. As shown in Figure 3A,B, their imaging system includes an sCMOS double-shutter camera offering a resolution of 2560 × 2160 pixels at a dynamic range A/D of 16 bit and a double-pulse laser of Quantel EverGreen 70 mJ working at a wavelength of 532 nm at a 15 Hz repetition rate. Harzallah et al. proposed an imaging system for coupled kinematic and thermal field measurements, as shown in Figure 4. The imaging system was equipped with two continuous high-power LEDs, a high-speed camera, Fastcam SA3, and an infrared camera, FLIR SC7000. The kinematic and thermal images can be obtained at the same time, but the only drawback is that the image quality is not good enough to distinguish between the cutting tool and the chip.

Zhang et al. conducted several investigations to obtain chip formation and shear zone information based on in situ imaging. They developed several imaging systems, including (1) a high-speed camera (PCO.dimax HD) with a continuous white laser for low-speed cutting as shown in Figure 5 and (2) a double-shutter camera (PCO.pixelfly) with pulsed LEDs for high-speed cutting as shown in Figure 6. Regarding the image quality, they found that the LED lighting source is better than laser. A comparison of the apparatus and the setting parameters is shown in Table 2.

### 2.2 Digital image processing technique

Digital image processing techniques are used to obtain the dynamic information from a series of images recorded by imaging systems. PIV and DIC are two of the most effective techniques. Traditionally, PIV has been widely used to track the instantaneous velocity of particles in fluids. Meanwhile, high-speed PIV can be applied in aerodynamics, hydrodynamics, and even biomedical research. DIC is very similar to PIV in terms of the principle and the...
implementation algorithm, usually used in experimental solid mechanics to obtain information on the deformation field. Over the past few years, the DIC technique has been extensively investigated. A detailed review of PIV and DIC can be found in the literature.34 Reu and Miller49 discussed the challenges in the application of high-speed DIC for dynamic events. Pan et al.50 and Khoo et al.51 systematically summarized the fundamentals and development of DIC. Nowadays, the DIC technique is widely applied in metal cutting processes. Several approaches based on DIC have been developed as described below. However, the frame rate of the camera needs to be high enough to reduce the motion blur and improve PIV or DIC correlation coefficients. It is suggested that the maximum plastic strain increment between the subsequent images needs to be less than 0.2 to eliminate the calculation error caused by distortion.18

Local subset-based DIC52–55 is a classical approach to calculate points of the region of interest (ROI) one by one to determine displacements. Namely, each speckle pattern is analyzed independently. A schematic illustration of the local subset-based DIC approach principle is shown in Figure 7. In this approach, the analysis starts by selecting a reference subset centered at the point in ROI and matching its target counterpart in the deformed image with maximum similarity. Then, a displacement mapping function that quantifies the degree of similarity between two subsets is used to optimize the position and shape of the target subset. Finally, the desired
**FIGURE 4** Visual and infrared coupled imaging of the cutting process developed by Harzallah et al. Reproduced with permission.\textsuperscript{41} Copyright 2018, Elsevier

**FIGURE 5** Imaging setup (A) of the low orthogonal cutting process by a high-speed camera with (B) the structure developed by Zhang et al. Reproduced with permission.\textsuperscript{38} Copyright 2017, ASME

**FIGURE 6** (A) Imaging setup of the cutting process based on a double-shutter camera and pulsed high-power LEDs and (B) working principle developed by Zhang et al. Reproduced with permission.\textsuperscript{18} Copyright 2021, Elsevier. LED, light-emitting diode
displacement gradients can be obtained. This approach has a simple principle, high efficiency, and high accuracy, but the inter-subset continuity is lost during the correlation process.

Another widely used approach is the global finite-element (FE)-based DIC. The FE-DIC approach calculates displacements of all nodes at the same time. In this respect, global FE-DIC overcomes the discontinuity of the inter-subset in local subset-based DIC. A schematic representation of the principle of the global FE-DIC approach is shown in Figure 8. The entire ROI is first discretized into finite elements connected by nodes. Next, a correlation function needs to be defined for mapping all the elements in the reference image to the corresponding elements in the deformed image. Finally, the displacement gradients of all nodes are optimized simultaneously by maximizing the correlation function. More detailed information on the algorithm of local and global approaches is summarized in the literature.

3 | DYNAMICS OF CHIP FORMATION

A better understanding of chip formation mechanisms is necessary. Chip formation leads to improvements in the surface integrity and functional performance and life of the components. Imaging systems combined with digital imaging processing techniques are suitable for analyzing the dynamic cutting processes due to their accessibility and processing time. In this section, chip formation mechanisms, tribological behavior in metal cutting, strain, strain rate, and stress fields in the deformation are discussed.

3.1 | Chip formation mechanism

3.1.1 | Finite element modeling to study chip formation

Metal cutting is a material removal process, in which external energy is applied to the cutting system, causing the separation of the layer being removed. The finite element method (FEM) is an effective approach adopted in the manufacturing field. The FE approach not only reduces the expensive and time-consuming experimental testing but also allows analysis of the mechanisms of chip formation. Obikawa et al. reported that FEM can be applied to simulate and analyze the mechanism of discontinuous/serrated chip formation process in orthogonal cutting. Childs simulated metal cutting to investigate the...
influence of thermal softening and strain hardening coefficients of the constitutive model on the mechanism of chip formation.

Priyadarshini et al.66 presented a brief overview of the application of FEM to metal cutting simulation. Recently, a detailed review67 suggested that the causes and effects of chip segmentation need to be considered in the simulation to improve tool life prediction and select the optimal cutting parameters for improved product quality. Guo et al.68 investigated the chip formation mechanism using FEM considering a damage model. They presented to simulate discontinuous chips in high-speed machining (Figure 9A). Using numerical simulation, Duan et al.69 found that the degree of chip segmentation and the space between each chip segment increase with decreasing tool rake angle (Figure 9B). The effect of cutting speed on chip characteristics was investigated by Li et al.,70 and the simulation of microcrack during serrated chip formation was achieved through FEM (Figure 9C). Xu et al.71 predicted the microstructure of serrated chips by FEM and cellular automata methods considering grain refinement (Figure 9D).

3.1.2 | Experimental methods to observe the chip formation process

There are a large number of experimental studies on the chip formation process using several techniques. In the earlier days of metal
cutting research, the quick-stop device was used to investigate the chip formation process. Using this technique, Komanduri et al.\(^7^2,7^3\) found discontinuous chips for cutting speeds below 30 m/min (Figure 10B). The chip segmentation process was found to be the result of instabilities in the cutting process and is further augmented by the dynamic response of part of the machine tool structure. Jaspers et al.\(^7^4\) indicated that the quick-stop device was well suited to study the chip formation process (Figure 10C). Vyas and Shaw\(^7^5\) used a quick-stop device and drew the conclusion that the tendency for saw-tooth chip formation increases with the cutting speed, owing to the increase of the strain rate (Figure 10D). Using a quick-stop device also enabled investigation of the deformation in the primary and secondary deformation zones, and observation of the built-up edge and the stagnation point. However, the design of the quick-stop device required a significant amount of work, since a large force is required to retract the cutting tool or workpiece during experiments. In addition, the time-varying strain rate, strain, and temperature cannot be captured using this method. With the development of digital imaging techniques, the dynamics of the metal cutting process can be captured easily. Sutter et al.\(^7^6,7^7\) analyzed the geometrical characteristics of the chip by a photographic recording of the cutting process. It was shown that the radius of curvature of the chip and the tool–chip contact length are scaled by the uncut chip thickness (Figure 11A). Hijazi et al.\(^7^8\)
used multichannel gated-intensified cameras for capturing the chip–workpiece interface (Figure 11B). Recently, an advanced imaging technique using an in situ scanning electron microscope (SEM) cutting apparatus was used to characterize the dynamics of chip formation and machined surface morphology in sub-micron ultra-precision cutting, and the results indicated the effectiveness of the approach in validating the finite element modeling.

Udupa et al. demonstrated the unsteady plastic flow with folding transitions to a sinuous flow in the presence of a surface media chemical surface-active medium using high-speed in situ imaging (Figure 12A). Ahmed et al. conducted a comprehensive investigation of built-up edge formation during machining (Figure 12B). They noticed that the built-up edge structure obtained at the highest cutting speed was thinner than the lowest one. The differences in chip morphology during machining were investigated by Davis et al. They used the DIC technique to determine the shear strain rate during chip formation. They found that if the shear strain rate distribution contains a shift in the chip flow direction, the chip morphology has a saw-tooth pattern; otherwise, the chip formation is continuous.

In summary, the numerical simulation of metal cutting using advanced material constitutive and contact models can predict the chip morphology quite well, but some phenomena such as sinuous flow and built-up edge still cannot be simulated. However, although the experimental technique of the quick-stop device has been fully developed, this method can hardly avoid large impact during the
experiments, and the spatial resolution is not of high quality. Finally, because of the high-speed camera devices and the DIC algorithm, the in situ imaging technique is easy to implement and provides the workpiece deformation history, including sinuous flow and built-up edge during chip formation. On the other hand, a minor disadvantage of the imaging technique is the high cost of the equipment.

3.2 | Tribological behavior in metal cutting

Contact between bodies is encountered in many engineering applications. In metal cutting, the tool–chip and tool–workpiece contact significantly influences chip formation. Numerous analogy experiments have been developed to obtain the friction coefficient and to
formulate extended contact models by varying the sliding velocity, temperature, and normal stress. Astakhov et al.\textsuperscript{85} discussed the tribological condition during cutting in detail. Details and description of tool–chip friction are shown in Figure 13A. Grzesik et al.\textsuperscript{86} conducted cylinder-on-disc experiments to investigate the friction behavior of three wear-protective coatings for dry machining applications. Zemzemi et al.\textsuperscript{87} characterized the tribological behavior at the tool–workpiece interface with various cutting tools. They showed that the friction coefficient decreases with the sliding velocity or contact pressure, and there exists a threshold effect of the contact pressure, that is, beyond a critical value of contact pressure, friction coefficients are no longer sensitive to contact pressure. Puls and Klocke\textsuperscript{88} analyzed the tribological behavior of the tool–chip interface. They developed an experimental setup based on orthogonal cutting tests using an extreme negative rake angle, which avoids chip formation. They found that the friction coefficient is strongly dependent on the sliding velocity. Peng et al.\textsuperscript{22} used a similar experimental setup as Puls and Klocke and proposed an advanced friction model as a function of the sliding velocity, contact temperature, and normal contact pressure. Rech et al.\textsuperscript{89,90} conducted several investigations to understand the tribological phenomena at the tool–chip/workpiece interfaces. They developed a new tribometer for determining the friction and heat partition coefficients under similar contact conditions as those observed in metal cutting (Figure 13B).

The tribological behavior at the tool–chip interface is more complex than of the tool–workpiece interface. One classical contact model for the tool–chip interface was proposed by Zorev,\textsuperscript{91} who divided the tool–chip contact into plastic zone (near the tool tip) and a sliding zone (elastic). A review presented by Melkote et al.\textsuperscript{92} summarized the friction coefficients for metal cutting modeling. Special attention was paid to the contact model and to the determination of the coefficients. However, it was not mentioned in this review that some researchers used imaging techniques to directly observe the tool–chip contact. In the early 2000s, Madhavan and Chandrasekar\textsuperscript{93} carried out in situ experimental studies of the tool–chip interface using transparent tools and optical microscopy, capturing images on videotape. They showed that metal deposition on the rake face occurs near the chip curls out of contact with the tool. Hwang et al.\textsuperscript{94} performed a study similar to that of Madhavan and Chandrasekar. They used transparent sapphire tools in combination with a CCD-based high-speed imaging system for direct observation of the chip–tool interface (Figure 14). Furthermore, velocity profiles obtained by PIV confirmed the retardation of the chip in the chip root, indicating that sticking friction occurred. One of the drawbacks of these experiments is the slow cutting speed used in the cutting tests (0.5 mm/s). Recently, Denkena et al.\textsuperscript{95} analyzed the tribological mechanisms in machining via high-speed chip formation recording. They found, for different tool coating and cutting speeds (50–150 m/min), a significant influence of the sliding speed at the tool–chip interface on the friction coefficient, as shown in Figure 15. Therefore, with the advanced in situ imaging technique, not only can the tribological phenomena during the cutting process be observed but also the friction coefficient can be determined for further use in the numerical simulation of metal cutting.

3.3 Strain and strain rate fields

3.3.1 Microgrids analysis

Metal cutting is often considered in the literature as a severe plastic deformation (SPD) process. The strains in shear zone may reach 1–2, and the strain rate can reach up to $10^5$s$^{-1}$, which influences the dynamics of chip formation considerably. In this respect, the determination of the strain/strain rate in metal cutting is one of the key points for both theory and application. To address this issue, various analytical approaches had been developed in the early years of metal cutting research, mainly based on the Merchant\textsuperscript{96} shear plane model.

![Figure 14](A) Photographic images of the chip–tool interface during cutting and (B) the velocity profile. Reproduced with permission.\textsuperscript{94} Copyright 2011, Springer Nature
Another classical analytical approach to describe the deformation in chip formation is the parallel-sided shear zone model proposed by Oxley and Shaw. Although analytical models are easy to understand and implement, the cutting mechanism is oversimplified. As already mentioned in Section 3.1, numerical simulation of metal cutting can also be used to obtain the strain/strain rate, but some phenomena such as built-up edge and sinuous flow still cannot be simulated. The two most popular experimental methods used for strain/strain rate field measurements during orthogonal cutting are (1) microgrids analysis and (2) in situ imaging using the DIC technique. The microgrids technique involves printing predefined grid squares on the workpiece surface. By analyzing the distortion of the deformed grids after the orthogonal cutting test, the equivalent plastic strain field can be determined. As early as 1965, Bitans et al. used square grids on a submillimeter scale to study the relationship between the shear angle and the rake angle. They found that the plastic shear zone becomes thicker at a higher rake angle. Childs et al. used the same technique to study the material flow in machining. Ghadbeigi et al. developed ultra-fine microgrids (10 µm pitch, line width less than 1 µm) using electron beam lithography on the workpiece surface. Orthogonal cutting tests were carried out, and the calculated maximum local plastic strain close to the machined surface reached 2.2. On the other hand, Pujana et al. used high-speed filming to obtain a sequence of frozen images of chip formation using a workpiece marked with square grids. The results are shown in Figure 16A. Recently, Sela et al. created physical microgrids in a workpiece and measured strain and strain rate fields in the primary deformation zone using a single image with the distorted grids, as shown in Figure 16B. The microgrids were observed to have severe distortion, and the results of strain and strain rate were not smooth enough. Moreover, the fabrication of microgrids on the workpiece surface is complex, and due to the low spatial resolution, calculation of the strain near the tool cutting edge can be inaccurate.

### 3.3.2 In situ imaging with the DIC technique

In situ imaging and the DIC technique have been successfully implemented for characterizing the strain and strain-rate distributions in metal cutting. Using these techniques, Guo et al. obtained high strain (Figure 17A) with a low cutting speed during chip formation. They found that chip flow is steady and laminar at large negative rake angles. As the rake angle increases, the chip morphology changes from discontinuous to segmented, and then to a continuous chip. Crack initiation occurs at the prow-free surface for a strain of approximately 0.8 in brass, providing a strain-controlled failure criterion. List et al. focused on high-speed cutting of a mild steel to analyze the strain and strain rate distributions by observing the chip using a high-speed camera system. Thimm et al. studied the chip formation and the shear strain rate of AISI 1045 steel at several cutting speeds, uncut chip thickness, and rake angle using double-frame camera devices. Harzallah et al. described the use of a bispectral imaging apparatus to obtain the kinematic and thermal fields simultaneously in orthogonal cutting. They found that the region of high strain rate is fixed in space and their values only vary slightly over time (see Figure 17B) due to the cyclic nature of chip formation. Davis et al. studied the strain progression within the primary deformation zone in the chip flow direction during machining (Figure 17C). A similar work was presented by Yadav and Sagapuram; they captured the strain history along the chip flow, which is shown in Figure 17D. Zhang et al. described the workpiece behaviors accurately during machining by means of in situ imaging. Different levels of strain/strain rate were obtained by varying the rake
angle, cutting speed, and initial workpiece temperature. Figure 17E shows an example of the strain rate field obtained by these researchers. Bergs et al. also presented the in-process analysis of the strain/strain rate in the primary deformation zone using the imaging technique, as shown in Figure 17F. The in situ imaging and DIC techniques have contributed toward better understanding of the chip formation mechanism by making it convenient and easy to obtain intermediate physical information, including velocity, strain, and strain rate fields.

3.4 Stress field

The stress fields generated during cutting are also of great value for studying cutting mechanisms, improving surface integrity, and reducing tool wear. However, although the research on strain and strain rate in the cutting process is extensive, as previously mentioned, mapping the stress field in the deformation zone using the in situ imaging technique remains a challenge because of its considerable sensitivity to experimental result noise.

To address this issue, some researchers used Oxley’s model, as shown in Figure 18A, in orthogonal cutting. Using this model, the primary deformation zone is simplified and represented by a parallel-sided zone centered about the straight-line AB shown in Figure 18A. Based on this assumption, the von-Mises stress can be calculated based on the DIC-measured equivalent strain and strain rate with a given constitutive model. Combined with the shear angle determined by the strain rate field, the plastic stress distribution in the primary shear zone is obtained, as shown in Figure 18B. In addition, using the parallel-sided shear zone to characterize the deformation in the primary shear zone, Huang et al. proposed a model-based DIC algorithm to reconstruct the stress field. On the other hand, efforts have been made to modify the image technique for stress field determination. Zhang adopted mechanical equilibrium equations to modify the hydrostatic pressure field to compensate for the inaccuracy of the measured elastic deformation. In a subsequent publication by the same author, a FEM analysis was performed to optimize the velocity field determined by DIC and to generate the stress field, as shown in Figure 19A,B, respectively.

Instead of determining the maximum shear stress direction by the shear band or the modified displacement field, Yang et al. proposed a new method inspired by the slip-line model, in which the flow stress of the work material is calculated based on the DIC-measured strain and strain rate. The stress equilibrium, friction law along the tool–chip interface, and the traction-free boundary condition along the uncut chip surface are all then taken into account to determine the stress fields. The obtained stress fields in terms of the shear flow stress $k$, the hydrostatic pressure $p$, and the angle of maximum shear stress $\theta$ are shown in Figure 20A–C. In addition, Figure 20D shows the slip lines calculated from the maximum shear stress angle. It can be found that the $\beta$ slip lines are concave near the...
cutting edge and convex near the free surface, which is consistent with the classic slip-line models of metal cutting.

4 | SURFACE INTEGRITY CHARACTERIZED BY THE IMAGING TECHNIQUE

Surface integrity including surface roughness, residual stress, and subsurface plastic deformation is a critical indicator of the performance and reliability of the final machined product. As a powerful in situ method, the imaging technique has been used in various investigations to provide valuable insight into the surface alteration induced by the machining process or to improve the prediction of surface integrity. In this section, thermo-mechanical loadings, subsurface plastic deformation, and identification of the constitutive parameters are discussed.

4.1 | Thermo-mechanical loadings

Traditionally, most studies on machining surface integrity start from the machining parameters and aim to establish their relationship with
FIGURE 18  (A) Oxley’s parallel-sided primary shear zone model. Reproduced with permission.\textsuperscript{108} Copyright 2009, Elsevier. (B) Mises stresses along the shear plane derived from the constitutive model. Reproduced with permission.\textsuperscript{109} Copyright 2019, ASME

FIGURE 19  (A) Stress field obtained by hydrostatic pressure modification. (i) Normal stress in the x direction, (ii) shear stress in the xy direction, and (iii) normal stress in the y direction. Reproduced with permission.\textsuperscript{38} Copyright 2017, ASME. (B) Hybrid digital image correlation–finite element modeling approach. Reproduced with permission.\textsuperscript{3} Copyright 2018, ASME. (i) Normal stress in the x direction, (ii) shear stress in the xy direction, and (iii) normal stress in the y direction
the induced surface integrity (Figure 21 correlation A). However, the established correlations are only valid in a limited range of cutting conditions; therefore, this approach leads to extensive experiments or simulations. To address this challenge, some researchers attempted to study the influence of the external loads on the surface integrity in the machining process (Figure 21 correlation B). As a result, several analytical models\textsuperscript{111–113} and hybrid models\textsuperscript{114–118} were developed. Because determination of the thermal and mechanical loadings in the cutting process is an important topic, some investigations related to the imaging technique are discussed below.

Harzallah et al.\textsuperscript{41} used a high-speed camera and an infrared camera to measure the kinematic and thermal fields simultaneously in the cutting process. Then, from an energy point of view, the heat flux and consumed energy in the deformation zone are obtained by a sophisticated postprocess, and used to study the influence of the thermal phenomenon on the surface integrity.

Baizeau et al.\textsuperscript{120} proposed a method to calculate the mechanical load by comparing the displacement in the elastic region of the work material using the Flamant–Boussinesq solution. The latter represents the theoretical displacement induced by force combination applied to an elastic semi-infinite medium under the plane strain condition, and the former represents the displacement determined using the global DIC technique.

In the last decade, to describe the underlying mechanism of the surface integrity generation more conveniently and adequately, a new concept named “Process Signature” was proposed by Brinksmeier et al.\textsuperscript{121} in 2011. Instead of the machining parameters or external loads, process signature only takes the internal loads such as stress, strain, temperature, and their gradients into account, and then physics-based correlations between these internal loads and the resulting material modifications are established (Figure 21 correlation 3). It is claimed that process signature can not only predict the surface integrity in the machining process but can also provide a knowledge-based approach to determine the optimum process parameters for the desired surface integrity. As an effective method to obtain in situ kinematic information, the imaging technique can be used to determine the internal loads during the cutting process and correlate them with the corresponding material modifications (Figure 22).

### 4.2 Subsurface plastic deformation

As one of the important topics in surface integrity research, evaluation and understanding of the subsurface plastic deformation have attracted a lot of attention, with the imaging technique becoming a more popular experimental method. Imaging techniques and DIC have been used to obtain subsurface deformation in orthogonal cutting (two-dimensional machining), where the lateral surface of the workpiece and the cutting tool are almost in the same plane, and as a consequence, the subsurface deformation can be captured using the imaging technique. Besides, the width of the cutting edge should be larger than the thickness of the workpiece. Different from the ex situ experimental approach such as the microgrids method, the imaging technique provides an in situ insight into the dynamic flow field and the evolution of deformation on the subsurface. Postprocessing via PIV\textsuperscript{122,123} revealed the folds and the sinuous nature of the near-surface flow in sliding, which is similar to the Kelvin–Helmholtz-type flow instabilities in fluids. The folds formed ahead of the interface and did not change much while traversing the contact region until they underwent stretching and rotation near the sliding tool tip as shown in Figure 23A. Mahato et al.\textsuperscript{124} determined the strain and strain rate fields in the workpiece sliding against a wedge indenter.
It is reported that the large initial strain in the workpiece and the high wedge incidence angle promote the formation of localized deformation in the form of a shear band as shown in Figure 23B. Furthermore, Guo et al.37 studied the occurrence of this instability and crack initiation in both sliding and cutting conditions, and developed a universal mechanism to determine the chip morphology.

Using a high-resolution imaging technique, many investigations have explored the dependence of subsurface deformation on the cutting parameters. For example, it was found that the more negative the tool rake angle, the more severe the subsurface plastic deformation.36,125–129 It was reported that different undeformed chip thicknesses generate a similar in-depth profile of the subsurface plastic strain with respect to the normalized depth, which was obtained by dividing the depth by the undeformed chip thickness as shown in Figures 24 and 25. Moreover, similarities between the deformation history of the chip and the near-surface region have also been reported.125–127,129

In addition to enabling the study of the surface integrity directly, the imaging technique can also offer full-field subsurface information for metal cutting modeling and simulation. On the one hand, it can be an effective way to validate or evaluate both the analytical and numerical-based models by comparing the predicted results with those measured experimentally. On the other hand, it can be widely used to improve hybrid models of surface integrity.131

As discussed above, use of imaging techniques has mainly been focused on studying the kinematic state on the subsurface, such as material flow and deformation. However, some recent publications have demonstrated direct links between the plastic strain components or eigenstrain in the subsurface and the residual stress and between the equivalent plastic strain and white layer formation.132 Therefore, it is expected that the imaging technique will have an extended range of applications in surface integrity research in the future.

4.3 Identification of the constitutive parameters

FEM plays an important role in the study of machining-induced surface integrity, whose accuracy is highly dependent on the ability to describe the mechanical behavior via an appropriate constitutive model. However, there are some limitations of the universally adopted split Hopkinson bar (SHB) tests in identifying the material’s constitutive parameters for machining simulation. First of all, the strain and strain rate involved in the cutting process are higher than those in SHB tests, so extrapolation to higher strains and strain rates...
is needed, leading to a significant error. Moreover, the state of stress in the material of the primary deformation zone in cutting cannot be reproduced by simple SHB compression tests using cylindrical specimens.\textsuperscript{4,18} To tackle these issues, some attempts have been made to use the cutting process itself as the material testing method to determine the coefficients of the constitutive model using an inverse approach.\textsuperscript{133–135} The main idea is to conduct the cutting experiment for different cutting parameters to generate the required range of strain, strain rate, cutting temperature, and state of stresses in the primary shear zone. Then, coefficients of the constitutive model can be identified by matching experimental measured stress distribution in primary shear zone to analytical results.

An analytical model assuming uniform distribution of the strain along the primary deformation zone is not consistent with reality. Therefore, the imaging techniques are used to accurately determine the strain and strain rate distributions in the first deformation zone. A summary of the imaging techniques used in the inverse approach to determine the coefficients of the constitutive model is presented in Table 3.

5 | SUMMARY AND FUTURE DIRECTIONS

This review summarizes the current state of the art of the dynamics of the chip formation using imaging techniques along with their applications for surface integrity analysis. Significant progress has been made in the development of imaging techniques to study the strain and strain rate during the chip formation process. It has been implemented in the orthogonal cutting process of continuous and segmented chip formation and milling processes. In addition, the research community is actively engaged in research on stress calculation from the kinematic fields. The achievements can be summarized based on progress made in the following areas:

- Clear images of the cutting process to study serrated chip formation processes and workpiece stagnation point.
- Velocity fields to identify the built-up edge and the sliding speed between the tool and the chip.
- Strain rate and strain, particularly in the primary shear zone and the machined surface.
- Stress and temperature calculated based on the thermo-mechanical coupled analysis of the plastic deformation of the elasto-plastic material.

The success of the investigations conducted in the following research areas is attributed to the measured information:

- **Inverse identification of the work material constitutive parameters.** With the measured strain, strain rate, stress, and derived temperature in the primary shear zone, the material behavior in the high strain rate, strain, and the rate of temperature increase during the cutting process have been studied.
- **Identification of tool-chip friction.** Through measurement of the sliding velocity of the work material near the cutting tool edge and the derivation of the stress through stepwise increment of the cutting depth, the sliding velocity-dependent friction coefficient has been determined.
- **Slip-line construction.** Because of the measured strain rate field, the slip-line field in the main deformation zone has been successfully identified.
- **Numerical confrontation.** The finite-element simulated strain rate field has been validated by the in situ imaged result.

Nevertheless, the imaging techniques need further development as below:

- **Measurement of the plastic deformation along the adiabatic shear zone, tool–chip friction, and machined surface.** In these regions, extensive plastic deformation occurs in a narrow zone compared with the primary shear zone, which requires higher resolution and frame rate as well as lighting.
- **Determination of the separation zone.** The separation of the chip from the work material near the cutting tool edge poses a major challenge to the image correlation algorithm since it is normally continuous subset-based. Therefore, subset-splitting-based image correlation should be adopted to address this challenge.
- **Lubricants and cooling.** In the practical machining process, lubricants or cooling are generally used. The possible obstruction and contamination to the imaging process should be considered to study the effects of the lubricants or cooling on the cutting process.
- **Three-dimensional cutting process.** The in situ imaging techniques should be updated and adjusted to study the oblique cutting process that occurs in the practical turning and milling processes.
- **Experimental validation of measurement results.** There are many factors influencing the measurement accuracy of the in situ imaging techniques. Experimental validation using more accurate methods such as the microgrids method should be conducted.

In future research, the eigenstrains or plastic strain components during the machining process, which are critical to the prediction of machined surface integrity, can be determined using the derivation in situ imaging technique. Future studies can be focused on the following topics:

- **Derivation of the thermo-mechanical loading.** With the calculated stress field and temperature fields, the thermo-mechanical loading applied on the primary and tertiary shear zones can be calculated.

### TABLE 3

| Workpiece material                  | Adopted constitutive model | Cutting condition                  |
|-------------------------------------|-----------------------------|-----------------------------------|
| Al 7075-T6 [18]                     | \( \sigma = g(\varepsilon)\Gamma(\dot{\varepsilon})\Theta(T) \) | Rake angle from 6.4 to 24.3°, cutting speed from 30 to 300 m/min, uncut chip thicknesses from 0.2 to 0.25 mm, and preheating temperature from 11 to 338.3°C |
| NiAl                               | \( \sigma = (A + B\varepsilon^p) \left( 1 + C \ln \frac{\varepsilon}{C_0} \right) \left( 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^{1+n} \right) \) | Cutting speed from 30 to 180 m/min, uncut chip thicknesses from 0.1 to 0.15 mm |
| AISI 1045 [136]                     | \( \sigma = (A + B\varepsilon^p) \left( 1 + C \ln \frac{\varepsilon}{C_0} \right) \left( 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^{1+n} \right) \) | Rake angle from -6 to 6°, cutting speed from 80 to 160 m/min, and uncut chip thicknesses from 0.1 to 0.2 mm |
| Al 6061-T4 [137]                    | \( \sigma = A + B\varepsilon^p \) | Uncut chip thicknesses from 0.08 to 0.1 mm |
• Mechanical aided DIC. Mechanical equilibrium equations, the material constitutive model, and geometric equations can be used to formulate the finite element equations. Together with the image subset pixels used in the DIC, the mechanical admissible kinematic field can be derived including the eigenstrains.

AUTHOR CONTRIBUTIONS

Guangchao Nie was involved in the conceptualization, methodology, investigation, and formal analysis of the study, and writing—original draft of the manuscript. Zhengyan Yang was involved in the conceptualization, methodology, investigation, and formal analysis of the study, and writing—original draft of the manuscript. Dong Zhang was involved in the conceptualization of the study, and writing—review and editing of the manuscript. Xiaoming Zhang was involved in the conceptualization, investigation, and supervision of the study, writing—review and editing of the manuscript, project administration, and funding acquisition. José Outeiro was involved in the conceptualization, investigation, supervision of the study, and writing—review and editing of the manuscript. Han Ding was involved in the conceptualization and supervision of the study, and writing—review and editing of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no data sets were generated or analyzed during the current study.

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REFERENCES

1. Merchant ME. Basic mechanics of the metal-cutting process. J Appl Mech. 1944;11(3):A168-A175.
2. Oxley PLB. The Mechanics of Machining: An Analytical Approach to Assessing Machinability. Ellis Horwood Ltd; 1989:242.
3. Zhang D, Zhang X-M, Ding H. Hybrid digital image correlation–finite element modeling approach for modeling of orthogonal cutting process. J Manuf Sci Eng Trans ASME. 2018; 140(4):041018.
4. Outeiro J, Umbrello D, M’Saouli R, Jawahir I. Evaluation of present numerical models for predicting metal cutting performance and residual stresses. Mach Sci Technol. 2015;19(2):183-216.
5. Dewhurst P. On the non-uniqueness of the machining process. Proc R Soc London A Math Phys Sci. 1978;360(1703): 587-610.
6. Lee E, Shaffer B. The theory of plasticity applied to a problem of machining. J Appl Mech Trans ASME. 1951;18(4):405-413.
7. Fang N, Jawahir I. Analytical prediction of the chip back-flow angle in machining with restricted contact grooved tools. J Manuf Sci Eng Trans ASME. 2003;125(2):210-219.
8. Fang N, Jawahir I. An analytical predictive model and experimental validation for machining with grooved tools incorporating the effects of strains, strain-rates, and temperatures. CIRP Ann. 2002; 51(1):83-86.
9. Fang N. Slip-line modeling of machining with a rounded-edge tool—Part I: new model and theory. J Mech Phys Solid. 2003;51(4): 715-742.
10. Fang N. Slip-line modeling of machining with a rounded-edge tool—Part II: analysis of the size effect and the shear strain-rate. J Mech Phys Solid. 2003;51(4):743-762.
11. Karpat Y, Özel T. Mechanics of high speed cutting with curvilinear edge tools. Int J Mach Tools Manuf. 2008;48(2):195-208.
12. Ren H, Altintas Y. Mechanics of machining with chamfered tools. J Manuf Sci Eng Trans ASME. 2000;122(4):650-659.
13. Karpat Y, Özel T. Analytical and thermal modeling of high-speed machining with chamfered tools. J Manuf Sci Eng Trans ASME. 2008; 130(1):011001.
14. Hu C, Zhuang K, Weng J, Zhang X, Ding H. Cutting temperature prediction in negative rake-angle machining with chamfered insert based on a modified slip-line field model. Int J Mech Sci. 2020;167: 105273.
15. Zhuang K, Fu C, Weng J, Hu C. Cutting edge microgeometries in metal cutting: a review. Int J Adv Manuf Technol. 2021;116: 2045-2092.
16. Jin X, Altintas Y. Slip-line field model of micro-cutting process with round tool edge effect. J Mater Process Technol. 2011;211(3): 339-355.
17. Uysal A, Jawahir I. Validation of the slip-line model for serrated chip formation in orthogonal turning under dry and MQL conditions. Proc CIRP. 2019;82:124-129.
18. Zhang D, Zhang X-M, Nie G-C, Yang Z-Y, Ding H. Characterization of material strain and thermal softening effects in the cutting process. Int J Mach Tools Manuf. 2021;160:103672.
19. Ugolimnighta NE, Khoshdarregi M, Ojo OA. Analysis and constitutive modeling of high strain rate deformation behavior of Haynes 282 aerospace superalloy. Mater Today Commun. 2019;20:100545.
20. Shams A, Mashayekhi M. Improvement of orthogonal cutting simulation with a nonlocal damage model. Int J Mech Sci. 2012;61(1):88-96.
21. Liu J, Bai Y, Xu C. Evaluation of ductile fracture models in finite element simulation of metal cutting processes. J Manuf Sci Eng Trans ASME. 2014;136(1):011010.
22. Peng B, Bergs T, Schraknepper D, Smigielski T, Klocke F. Development and validation of a new friction model for cutting processes. Int J Adv Manuf Technol. 2020;107(11):4357-4369.
23. Ding H, Shin YC. Multi-physics modeling and simulations of surface microstructure alteration in hard turning. J Mater Process Technol. 2013;213(6):877-886.
24. Mackerle J. Finite element analysis and simulation of machining: an addendum: a bibliography (1996–2002). Int J Mach Tools Manuf. 2003;43(1):103-114.
25. Mackerle J. Finite-element analysis and simulation of machining: a bibliography (1976–1996). J Mater Process Technol. 1999;86(1-3): 17-44.
26. Harzallah M, Pottier T, Gilblas R, Landon Y, Mousseigne M, Senatore J. Thermomechanical coupling investigation in Ti-6Al-4V orthogonal cutting: experimental and numerical confrontation. Int J Mech Sci. 2020;169:105322.
27. Stevenson M, Oxley P. An experimental investigation of the influence of strain-rate and temperature on the flow stress properties of a low carbon steel using a machining test. Proc Instit Mech Eng. 1970;185(1):741-754.
alloy during high speed machining. J Mater Process Technol. 2020; 286:116834.

72. Komanduri R, Brown RH. On the mechanics of chip segmentation in machining. J Eng Indus. 1981;103(1):33-51.

73. Komanduri R, Schroeder T, Hazra J, von Turkovich BF, Flom DG. On the catastrophic shear instability in high-speed machining of an AISI 4340 steel. J Eng Indus. 1982;104(2):121-131.

74. Jaspers S, Dautzenberg J. Material behaviour in metal cutting: strains, strain rates and temperatures in chip formation. J Mater Process Technol. 2002;121(1):123-135.

75. Vyas A, Shaw MC. Mechanics of saw tooth chip formation in metal cutting. J Manuf Sci Eng. 1999;121(2):163-172.

76. Sutter G. Chip geometries during high-speed machining for orthogonal cutting conditions. Int J Mach Tools Manuf. 2005;45(6):719-726.

77. Sutter G, Molinari A, List G, Bi X. Chip flow and scaling laws in high speed metal cutting. J Manuf Sci Eng. 2012;134(2):021005.

78. Hijazi A, Madhavan V. A novel ultra-high speed camera for digital image processing applications. Measur Sci Technol. 2008;19(8): 085503.

79. Wang Z, Zhang J, Xu Z, et al. Crystal plasticity finite element modeling and simulation of diamond cutting of polycrystalline copper. J Manuf Process. 2019;38:187-195.

80. Wang Z, Zhang J, Xu Z, et al. Crystal anisotropy-dependent shear angle variation in orthogonal cutting of single crystalline copper. Precis Eng. 2020;63:41-48.

81. Wang Z, Zhang J, Li G, et al. Anisotropy-related machining characteristics in ultra-precision diamond cutting of crystalline copper. Nanomaterials Metrol. 2020;3(2):123-132.

82. Udupa A, Viswanathan K, Saei M, Mann JB, Chandrasekar S. Material–independent mecanochemical effect in the deformation of highly-strain-hardening metals. Phys Rev Appl. 2018;10(1):014009.

83. Ahmed YS, Paiva JM, Bose B, Veldhuis SC. New observations on built-up edge structures for improving machining performance during the cutting of superduplex stainless steel. Tribol Int. 2019; 137:212-227.

84. Davis B, Dabrow D, Newrell R, et al. Chip morphology and chip formation mechanisms during machining of ECAE-processed titanium. J Manuf Sci Eng. 2018;140(3):031008.

85. Astakhov VP. (Ed.). Chapter 3 Tribology of the tool interface in machining. Tribology and Interface Engineering Series. Elsevier Ltd; 2006:52:124-219.

86. Grzesik W, Zalisz Z, Nieslon P. Friction and wear testing of multilayer coatings on carbide substrates for dry machining applications. Surf Coat Technol. 2002:155(1):37-45.

87. Zemzem F, Rech J, Salem WB, Dogui A, Kapsa P. Identification of friction and heat partition model at the tool tip-steel interfaces in dry cutting of an inconel 718 alloy with cbn and coated carbide tools. Adv Manuf Sci Technol. 2014;38(1):5-22.

88. Puls H, Klocke F, Lung D. A new experimental methodology to analyse the friction behaviour at the tool-chip interface in metal cutting. Proc Eng. 2012;4(4):349-354.

89. Rech J, Arrazola PJ, Claudin C, Bourbon C, Pusavec F, Kopac J. Characterisation of friction and heat partition coefficients at the tool-work material interface in cutting. CIRP Ann. 2013;62(1):79-82.

90. Rech J, Giovenco A, Bourbon C, Cabanettes F. Toward a new tri-voidological approach to predict cutting tool wear. CIRP Ann. 2018; 67(1):65-68.

91. Zorev NN. Inter-relationship between shear processes occurring along tool face and shear plane in metal cutting. Int Res Prod Eng ASME. 1965:42-49.

92. Melkote SN, Grzesik W, Outeiro J, et al. Advances in material and friction data for modelling of metal cutting. CIRP Ann. 2017; 66(2):731-754.

93. Madhavan V, Chandrasekar S, Farris TN. Direct observations of the chip-tool interface in the low speed cutting of pure metals. J Tribol. 2002;124(3):617-626.

94. Hwang J, Chandrasekar S. Contact conditions at the chip-tool interface in machining. Int J Precision Eng Manuf. 2011;12(2):183-193.

95. Denkena B, Krödel A, Beblein S. A novel approach to determine the velocity dependency of the friction behavior during machining by means of digital particle image velocimetry (DPIV). CIRP J Manuf Sci Technol. 2021;32:81-90.

96. Merchant ME. Mechanics of the metal cutting process. I. Orthogonal cutting and a type 2 chip. J Appl Phys. 1945;16(5):267-275.

97. Oxley PLB, Shaw MC. Mechanics of machining: an analytical approach to assessing machinability. J Appl Mech. 1990;57(1):253.

98. Bitsan K, Brown R. An investigation of the deformation in orthogonal cutting. Int J Mach Tool Des and Research. 1965;3(3):155-165.

99. Ghadbeigi H, Bradbury SR, Pinna C, Yates JR. Determination of micro-scale plastic strain caused by orthogonal cutting. Int J Mach Tools Manuf. 2008;48(2):228-235.

100. Lee S, Hwang J, Shankar MR, Chandrasekar S, Dale Compton W. Large strain deformation field in machining. Metall Mater Trans A. 2006;37(5):1633-1643.

101. Guo Y, Efe M, Moscoso W, Sagapuram D, Trumble KP. Chandrasekar S. Deformation field in large-scale extrusion machining and implications for deformation processing. Scripta Mater. 2012;66(5):235-238.

102. Guo Y, Chen J, Saleh A. In situ analysis of deformation mechanics of constrained cutting toward enhanced material removal. J Manuf Sci Eng. 2019:142(2).

103. List G, Sutter G, Bi XF, Molinari A, Bouthiche A. Strain rate and velocity fields determination at very high cutting speed. J Mater Process Technol. 2015;213(5):693-699.

104. Thimm B, Glavas A, Reuber M, Christ HJ. Determination of chip speed and shear strain rate in primary shear zone using digital image correlation (DIC) in linear-orthogonal cutting experiments. J Mater Process Technol. 2021;289:116957.

105. Davis B, Dabrow D, Ifju P, Xiao G, Liang SY, Huang Y. Study of the shear strain and shear strain rate progression during titanium machining. J Manuf Sci Eng Trans ASME. 2018;140(5):051007.

106. Yadav S, Sagapuram D. In situ analysis of shear bands and boundary layer formation in metals. Proc R Soc A Math Phys Eng Sci. 2020;476(2234):20190519.

107. Bergs T, Abouridaouane M, Meurer M, Beng D. Digital image correlation analysis and modelling of the strain rate in metal cutting. CIRP Ann. 2021;70:45-48.

108. Lalwani D, Mehta N, Jain P. Extension of Oxley’s predictive machining theory for Johnson and Cook flow stress model. J Mater Process Technol. 2009;209(12):5305-5312.

109. Zhang X-M, Zhang K, Zhang D, Outeiro J, Ding H. New in situ imaging-based methodology to identify the material constitutive model coefficients in metal cutting process. J Manuf Sci Eng Trans ASME. 2019;141(10):101007.

110. Yang Z-Y, Zhang X-M, Nie G-C, Zhang D, Ding H. A comprehensive experiment-based approach to generate stress field and slip lines in cutting process. J Manuf Sci Eng Trans ASME. 2021;143(7):071014.

111. Liang S, Su JC. Residual stress modeling in orthogonal machining. CIRP Annals. 2007;56(1):65-68.

112. Huang X-D, Zhang X-M, Ding H. A novel relaxation-free analytical method for prediction of residual stress induced by mechanical load during orthogonal machining. Int J Mech Sci. 2016;115:299-309.

113. Huang X-D, Zhang X-M, Leopold J, Ding H. Analytical model for prediction of residual stress in dynamic orthogonal cutting process. J Manuf Sci Eng Trans ASME. 2018;140(1).

114. Deng ZH, Zhang X-M, Yang Z-Y, Zhang D, Ding H. Modeling and analysis of residual stress in dynamic orthogonal cutting. Proc CIRP. 2020;67:485-490.
115. Mondelin A, Valiorgue F, Dumas M, et al. Development of a 3D hybrid modeling of residual stresses induced by grooving. Proc CIRP. 2019;82:400-405.

116. Mondelin A, Valiorgue F, Rech J, Coret M, Feulvarch E. Hybrid model for the prediction of residual stresses induced by 15-5PH steel turning. Int J Mech Sci. 2012;58(1):69-85.

117. Valiorgue F, Rech J. Numerical modeling of residual stresses in turning of a 27MnCr5 steel. Proc CIRP. 2016;45:331-334.

118. Valiorgue F, Rech J, Hamdi H, Gilles P, Bergheau JM. 3D modeling of residual stresses induced in finish turning of an AISI304L stainless steel. Int J Mach Tools Manuf. 2012;53(1):77-90.

119. Brinksmeier E, Meyer D, Heinzl C, et al. Process signatures—the missing link to predict surface integrity in machining. Proc CIRP. 2018;71:3-10.

120. Baizeau T, Campocasso S, Rossi F, Poulachon G, Hild F. Cutting force sensor based on digital image correlation for segmented chip formation analysis. J Mater Process Technol. 2016;238:466-473.

121. Brinksmeier E, Gläbe R, Klocke F, Lucca DA. Process signatures—an alternative approach to predicting functional workpiece properties. Proc Eng. 2011;19:44-52.

122. Sundaram NK, Guo Y, Chandrasekar S. Mesoscale folding, instability, and disruption of laminar flow in metal surfaces. Phys Rev Lett. 2012;109(10):106001.

123. Mahato A, Guo Y, Sundaram NK, Chandrasekar S. Surface folding in metals: a mechanism for delamination wear in sliding. Proc R Soc A Math Phys Eng Sci. 2014;470(2169):20140297.

124. Mahato A, Sundaram NK, Yeung H, Lukitsch M, Sachdev AK, Chandrasekar S. Quantitative in situ analysis of deformation in sliding metals: effect of initial strain state. Tribol Lett. 2015;60(3):1-11.

125. Guo Y, M’Saoubi R, Chandrasekar S. Control of deformation levels on machined surfaces. CIRP Annals. 2011;60(1):137-140.

126. Guo Y, Saldana C, Compton WD, Chandrasekar S. Controlling deformation and microstructure on machined surfaces. Acta Mater. 2011;59(11):4538-4547.

127. Calistes R, Swaminathan S, Murthy T, et al. Controlling gradation of surface strains and nanostructuring by large-strain machining. Scripta Mater. 2009;60(1):17-20.

128. Baizeau T, Campocasso S, Fromentin G, Rossi F, Poulachon G. Effect of rake angle on strain field during orthogonal cutting of hardened steel with c-BN tools. Proc CIRP. 2015;31:166-171.

129. Guo Y, Sagapuran D, Mahato A, M’Saoubi R, Trumble KP, Chandrasekar S. Understanding deformation on machined surfaces. Int Manuf Sci Eng Conf. 45806:V001T01A007.

130. Zhang D, Zhang X-M, Leopold J, Ding H. Subsurface deformation generated by orthogonal cutting: analytical modeling and experimental verification. J Manuf Sci Eng Trans ASME. 2017;139(9):094502.

131. Baizeau T, Rossi F, Poulachon G, Outeiro JC. Prediction of surface integrity using Flamant–Boussinesq analytical model. CIRP Ann. 2016;65(1):81-84.

132. Nie G-C, Zhang K, Outeiro J, et al. Plastic strain threshold determination for white layer formation in hard turning of AISI 52100 steel using micro-grid technique and finite element simulations. J Manuf Sci Eng Trans ASME. 2020;142(3):034501.

133. Tounsi N, Vincenti J, Otho A, Elbestawi M. From the basic mechanics of orthogonal metal cutting toward the identification of the constitutive equation. Int J Mach Tools Manuf. 2002;42(12):1373-1383.

134. Denkena B, Grove T, Dittrich MA, Niederwestberg D, Lahres M. Inverse determination of constitutive equations and cutting force modelling for complex tools using Oxley’s predictive machining theory. Proc CIRP. 2015;31:405-410.

135. Shi B, Attia H, Tounsi N. Identification of material constitutive laws for machining—Part I: an analytical model describing the stress, strain, strain rate, and temperature fields in the primary shear zone in orthogonal metal cutting. J Manuf Sci Eng Trans ASME. 2010;132(5):051008.

136. Thimm B, Steden J, Reuber M, Christ HJ. Using digital image correlation measurements for the inverse identification of constitutive material parameters applied in metal cutting simulations. Proc CIRP. 2019;82:95-100.

137. Zhang D, Zhang X-M, Ding H. Inverse identification of material plastic constitutive parameters based on the DIC determined workpiece deformation fields in orthogonal cutting. Proc CIRP. 2018;71:134-139.

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