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Review

Control over Multi-Scale Self-Organization-Based Processes under the Extreme Tribological Conditions of Cutting through the Application of Complex Adaptive Surface-Engineered Systems

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Abstract: This paper features a comprehensive analysis of various multiscale selforganization processes that occur during cutting. A thorough study of entropy production during friction has uncovered several channels of its reduction that can be achieved by various selforganization processes. These processes are (1) self-organization during physical vapor deposition PVD coating deposition on the cutting tool substrates; (2) tribofilm formation caused by interactions with the environment during operation, which consist of the following compounds: thermal barriers; Magnéli phase tribo-oxides with metallic properties at elevated temperatures, tribo-oxides that transform into a liquid phase at operating temperatures, and mixed action tribo-oxides that serve as thermal barriers/lubricants, and (3) multiscale selforganization processes that occur on the surface of the tool during cutting, which include chip formation, the generation of adhesive layers, and the buildup edge formation. In-depth knowledge of these processes can be used to significantly increase the wear resistance of the coated cutting tools. This can be achieved by the application of the latest generation of complex adaptive surface-engineered systems represented by several state-of-the-art adaptive nano-multilayer PVD coatings, as well as high entropy alloy coatings (HEAC).

Keywords: self-organization; cutting tools; PVD coatings; high entropy alloy coatings (HEAC)

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1. A Schematic Presentation of the Cutting Process

Figure 1 presents a schematic diagram of the numerous deformation and thermal processes that occur during metal cutting [1]. According to Figure 1, heat is generated during cutting due to the plastic deformation of the machined material in the primary and secondary shear deformation zones. The chips are formed as a result of workpiece material shear and flow on the rake surface of the tool (the secondary shear deformation zone). The formed chips undergo further plastic deformation in this zone, which results in temperature growth at the tool/chip interface. Since hard-to-machine materials (Inconels, Ti alloys, SDSS) mostly have low thermal conductivity, only a small portion of the friction-generated heat is transferred into the workpiece. A major portion of the heat is transferred into the body of the tool, whose rake surface temperature reaches 800–1000 °C, causing rapid wear [1].

Selforganization is one of the primary phenomena that occur during friction [2]. The phenomenon of selforganization with dissipative structure formation was discovered by I. Prigogine [3] and further studied by several well-known scientists, such as J.M. Lehn [4]. Both of them won the Noble Prize. Per Bak further expanded on their findings by establishing the concept of selforganized criticality [5]. All phenomena associated with selforganization happen throughout the entire cutting process. According to J. M. Lehn, 'multilevel hierarchical self-organization enables the progressive buildup of more and more complex systems in a sequential, temporally ordered fashion' [4]. Finding a practical application for dissipative nonequilibrium processes presents a major goal as well as a challenge for modern nanoscience and nanotechnology [4].

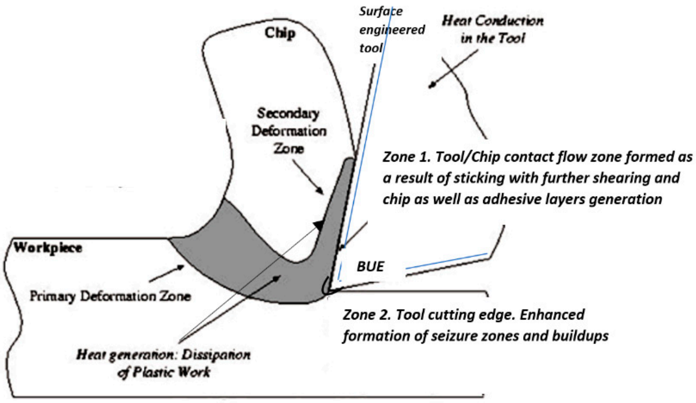


Figure 1. A schematic presentation of the cutting processes where several zones of selforganization are indicated [1].

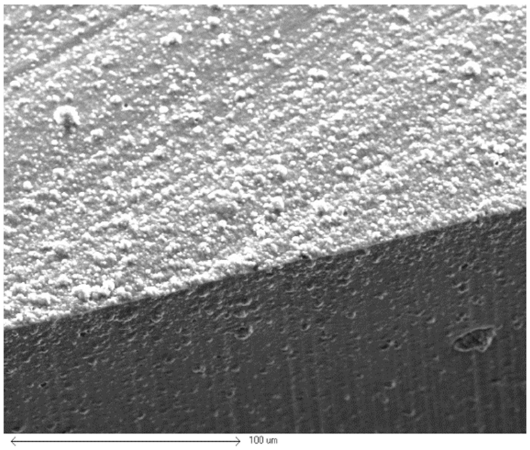
One such application can be found in the complex processes that take place during cutting with coated cemented carbide tools. Several selforganization processes develop simultaneously on multiple levels in such a complex tribosystem. These are the following:

1. Selforganization with the formation of highly nonequilibrium structures due to processes with negative entropy production during PVD coating deposition (a nanoscale (10–40 nm) process [6,7];
2. Formation of tribofilms as a result of the interaction between the surface-engineered layer with the surrounding environment, mostly through tribo-oxidation (a 2–5 nm nanoscale process). Tribofilms are dynamic surface spatial structures with temporal behavior [2,8];
3. Formation of phase transformation zones, such as strain-induced martensite zones within the layer of the chips (a microscale µm process) [9–17];
4. Formation of twinning zones on the worn surfaces of the cutting tools [18];
5. Formation of adhesive layers (a microscale µm process), which gradually progress from the adhesive interaction between the workpiece and the tool (Figure 2) to the formation of buildups over the course of a seizure process [19]. This results in the formation of a buildup edge (BUE), which is a macroscale (tens of microns) cyclic process combining selforganized criticality (SOC) and selforganization (SO) [18,20–25].

According to [3], selforganization is the process of dissipative structure formation. Dissipative structures are, by themselves, processes with negative entropy production. The formation of dissipative structures during selforganization is of particular interest to the field of tribology because a significant part of the friction energy is spent on their generation and maintenance. Therefore, selforganization minimizes the portion of energy that is spent on surface damage and wear. An attempt to describe and give characteristics to dissipative structures was given in [25].

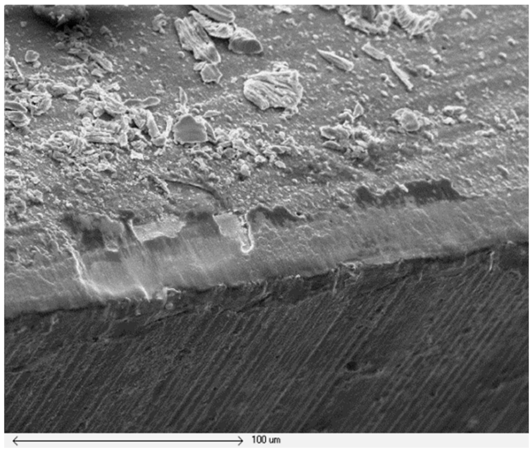
Numerous studies were performed on selforganization during friction [2]. However, various selforganization processes during cutting [26,27] have received little attention, aside from a limited number of initial studies. Although several models of selforganization processes during cutting have been proposed (2010–2015) [26,27], a further understanding of the complex physics associated with this phenomenon presents a highly promising future avenue of research.

Initial surface of the coated cutting tool.



(**a**)

Worn surface: initial formation of an adhesive layer.



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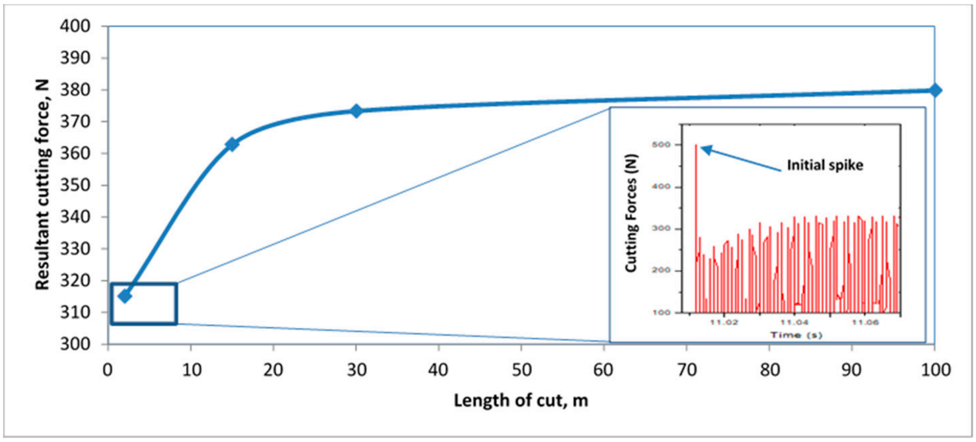

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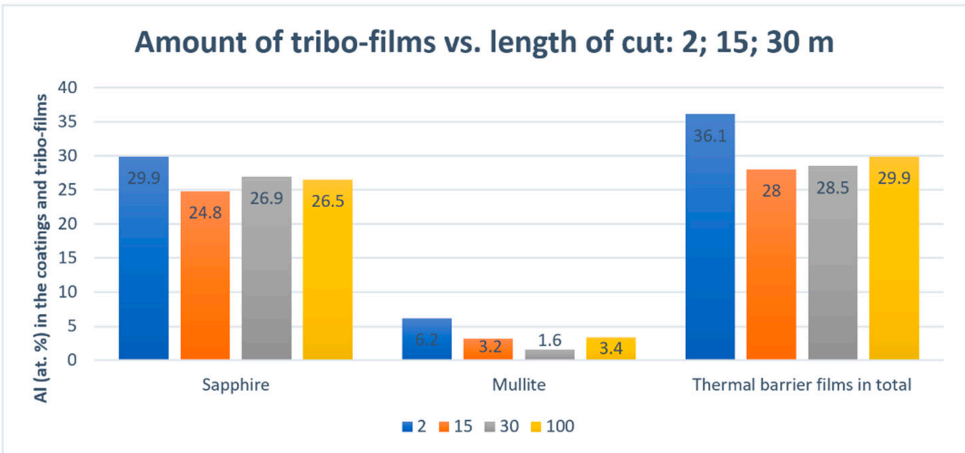


(**d**)

Figure 2. Flank wear vs. length of cut data for the ball nose end milling of H 13 hardened steel: (**a**) SEM image of the initial surface of the tool (before service); (**b**) SEM image of the worn surface of the tool (after a length of cut of 2 m); (**c**) the tool wear curve with cutting force data at the very beginning of cutting; (**d**) amount of tribofilms generated on the friction surface vs. length of cut (XPS data) [28].

2. Thermodynamic Analysis of Entropy Production

The following thermodynamic analysis may be very useful for gaining a better overall picture of the complicated tribological processes that take place during cutting.

As can be seen in Figure 1, various selforganization processes create multiple channels of reducing entropy production. Engineers can use these channels to improve the wear resistance of the tools. A thermodynamic analysis of entropy production was performed for this purpose.

As shown in detail in [2], the change in entropy of a frictional body (dS) is

$$\mathrm{d}S = \mathrm{d}S_i + \mathrm{d}S_e + \mathrm{d}S_m + \mathrm{d}S_f - \mathrm{d}S_w \quad (1)$$

Following differentiation with respect to time, Equation (1) in a stationary condition will be

$$\mathrm{d}S/\mathrm{d}t = 0 = \mathrm{d}S_i/\mathrm{d}t + \mathrm{d}S_e/\mathrm{d}t + \mathrm{d}S_m/\mathrm{d}t + \mathrm{d}S_f/\mathrm{d}t - \mathrm{d}S_w/\mathrm{d}t$$

or

$$\mathrm{d}S_w/\mathrm{d}t = \mathrm{d}S_i/\mathrm{d}t + \mathrm{d}S_e/\mathrm{d}t + \mathrm{d}S_m/\mathrm{d}t + \mathrm{d}S_f/\mathrm{d}t \quad (2)$$

For the cutting tool-chip interface, this equation should be slightly modified:

$$\mathrm{d}S_w/\mathrm{d}t = \mathrm{d}S_i/\mathrm{d}t + \mathrm{d}S_e/\mathrm{d}t \pm \mathrm{d}S_m/\mathrm{d}t - \mathrm{d}S_f/\mathrm{d}t$$

The physical description of each term is the following:

$\mathrm{d}S_i/\mathrm{d}t$ is the entropy production from the distribution of heat and other flows within a frictional body.

$\mathrm{d}S_e/\mathrm{d}t$ is the entropy production caused by external interactions, which could change due to the transfer of heat from a frictional surface with a higher temperature into the body of the cutting tool with a lower temperature. This leads to an increase in entropy production. Metal flow along the frictional surface causes the formation of chemical compounds (zones of sticking) and zones of phase transformation (see below $\mathrm{d}S_m/\mathrm{d}t$). Entropy can either increase or decrease depending on the processes occurring in zone 1 and 2, in addition to the workpiece material characteristics;

$\mathrm{d}S_m/\mathrm{d}t$ is the change in entropy due to the formation and decomposition of chemical compounds and phase transformations on the tool surface caused by entropy produced by the mass transferred from the frictional body in contact (the workpiece). Entropy change during tool-chip interaction can be either positive due to seizure [28] or negative when material transferred to the tool surface forms zones of phase transformation (strain-induced martensite zones) with increased hardness and reduced adhesiveness. The presence of lubricants (such as MnS) as well as interactions with the environment (tribo-oxidation) which lead to the formation of thermal barrier/lubricating tribofilms [28] on the surface of buildups and zones of adhesive interactions, also influence the change in entropy. From a thermodynamic point of view, the term $\mathrm{d}S_m/\mathrm{d}t$ of the process will be either positive or negative, depending on the change in free energy.

Another part of this equation, related to the term $\mathrm{d}S_m/\mathrm{d}t$, concerns surface engineering through the deposition of thin-film PVD ceramic coatings on the tool surface. The coating layer, if properly designed, represents a complex adaptive system [7,8], which can respond to frictional loads in its entirety, leading to efficient energy dissipation [8]. The coating layer's ability to dissipate energy within itself facilitates a decrease in the entropy produced by plastic deformation within the friction zone. Certain micromechanical characteristics of the coating layer could be measured to evaluate this generic property [2]. This is especially important for various machining applications, such as turning and end milling of hard-to-cut materials, which are characterized by cycles of buildup formation and detachment (SOC/SO processes) [18]. A reduction of the size and frequency of buildup formation [28–31] and consequent wear intensity can be achieved through the application of coatings with optimized characteristics.

$\mathrm{d}S_f/\mathrm{d}t$ is the change in entropy due to tribofilm formation caused by further tribo-oxidation.

dS_w/dt is the change in entropy due to the wear process (the "−" sign used in Equation (2) designates the by-products of the wear process exiting the frictional body along with their own entropy).

The change in entropy, dS_f/dt, could be either negative if nonequilibrium processes increase the free energy on the frictional surface, thereby reducing the entropy production within the frictional body [2], or it could be positive under equilibrium processes that decrease the free energy [2]. However, the sum of these terms, i.e., $dS_i/dt + dS_f/dt > 0$, is the general entropy production [2]. As follows from (2), lower entropy production corresponds to a lower dS_w/dt value. Bearing in mind that entropy is an additive value, a decreasing dS_w/dt, would indicate a decreasing wear rate. Nonequilibrium processes on the surface ($dS_f/dt < 0$) and the formation of thermal barrier/lubricating tribofilms due to material transfer from the workpiece caused by its further tribo-oxidation ($dS_m/dt < 0$) could also decrease the wear rate, at all other conditions being equal.

The formation of tribofilms results in the strongly nonequilibrium distribution of heat (temperature) compared to an equivalent state without them. As a consequence, the entropy production in coatings with thermal barrier/lubricating tribofilms formed during the cutting process is lower than that of the coatings without such tribofilms.

3. Selforganization Processes That Develop during Cutting with Coated Cemented Carbide Tools

3.1. Selforganization during PVD Coating Deposition on the Substrate of the Cutting Tool

The mechanics of the formation and growth of selforganized structures in PVD coatings have undergone extensive studies [7]. Multicomponent, multiphase thin films (such as nanoscale multilayers) generated under deposition conditions far from thermodynamic equilibrium [32] are good examples of such structures [33,34]. This type of selforganization is common in HEACs and similar adaptive PVD coatings capable of efficiently dissipating energy during friction and wear [35].

3.2. Various Selforganization Processes during Wear on the Surface of Cutting Tools

3.2.1. Tribofilm Formation

Tribofilms are an integral part of modern complex adaptive surface-engineered systems. This study is focused on tribofilms generated on the surface of cutting tools under specific machining conditions (machining of hard-to-cut materials) as a result of structural modification and interaction with the environment (mostly with oxygen from the air). Tribofilm formation on the surface of the coated tools is a straightforward selforganization process that can significantly reduce entropy production during cutting. According to Table 1, their formation considerably enhances the wear resistance of the tools.

Table 1. Types of tribofilms formed on the surface of coated carbide cutting tools [36–57].

Types of Tribofilms Formed, Which Control Tool Life		Coating Material	Cutting Conditions			Tool Life Improvement Compared with the Commercial Benchmark
Lubricious	**Thermal Barrier**		**Operation**	**Speed, m/min**	**Workpiece Material**	
Magnéli (W-O) phases		TiAlCrN/WN nano-multilayer	Ball nose end milling	220	H 13, hardened (Hardness of 53-55 HRC)	More than 2x that of a commercial TiAlCrN benchmark
Tribo-oxides with metallic properties at elevated temperatures Nb_20_5		TiAlCrN/NbN nano-multilayer	Ball nose end milling	300–400	H 13, hardened (Hardness of 53–55 HRC)	4x that of a commercial TiAlCrN benchmark
		TiAlN/NbN nano-multilayer	Turning, finishing operation	40	Inconel 718	60% greater than that of commercial TiAlN

Table 1. *Cont.*

Types of Tribofilms Formed, Which Control Tool Life		Coating Material	Cutting Conditions			Tool Life Improvement Compared with the Commercial Benchmark
Lubricious	Thermal Barrier		Operation	Speed, m/min	Workpiece Material	
Tribo-oxides, which transform to a liquid phase at high operating temperatures						
1. B_2O_3		TiB_2 monolayer	Turning, roughing operation	45	TiAl6V4	2x, as compared to commercial TiAlN benchmark
2. V_2O_5		AlTiN/VN nano-multilayer	Turning, finishing operation	150	TiAl6V4	50%, as compared to commercial TiAlN
3. MoO_3		AlTiN/MoN	Turning, finishing operation	40–60	Inconel 718	2x higher and above, as compared to commercial TiAlN
Lubricating/ thermal barriers						
1. Cr-O		CrN	Turning, roughing operation	45	TiAl6V4	2x higher and above, as compared to uncoated and commercial AlTiN
			Turning, roughing operation	150	TiAl6V4	2.3–1.45x higher and above, as compared to uncoated and commercial AlTiN
2. Si-O		TiAlSiN	Face milling	300	Cast iron	2x higher and above, as compared to uncoated tool
	Combination of Al_2O_3 Sapphires,Al6 Si2O13 Mullites,	TiAlCrSiYN/TiAlCrN multilayer	Ball nose end milling	500–600	H 13, HRC 52-54	2x higher and above, as compared to monolayer TiAlCrSiYN
	Y3Al5O12 Garnets, $AlCrO_x$ Rubies		Turning, Finishing operation	40	Inconel 718	2x higher and above, as compared to commercial AlTiN

Furthermore, tribofilm formation helps shift the system from the catastrophic tribological condition of seizure to a milder frictional condition [2], which will significantly enhance the wear resistance of the cutting tool.

The following tribofilms are formed during cutting:

3.2.2. Lubricating Tribo-Oxides

A. Magnéli phases.

Magnéli phases belong to the category of binary oxides. Magnéli phases are sub-stoichiometric compounds containing transitional metals that form a homologous series of Me_xO_{2y} compounds. These compounds contain planar lattice faults that generate crystallographic shear planes with reduced binding strength. In this way, lubrication is enhanced at elevated temperatures [36–42]. A typical example of these oxides is a high-temperature lubricant WO_3 with low shear strength [43,44]. The formation of such tribo-oxides can explain why uncoated carbide tools outperform tools with hard coatings such as AlTiN [45] during the machining of sticky Ti alloys.

B. Oxides with metallic properties at elevated temperatures.

A typical example of a tribo-oxide with metallic properties is Nb_2O_5. The mechanism of its function involves the ability to dissipate energy over the course of the machining process [46]. During friction, an excessive quantity of dislocations accumulates on the surface as a result of intensive plastic deformation happening there during machining [44].

A surface with metallic bonds has a higher ability to dissipate energy during friction, possibly due to the dislocations becoming more mobile within the surface layer of the oxide tribofilms. This is experimentally confirmed by the high intensity of plasmon peaks collected by the HREELS method from the worn area [46]. The emergence of more flexible and mobile dislocations facilitates stress relaxation within the friction zone and reduces the formation of an excessive number of defects on the surface [46]. This will, in turn, prevent the growth of surface energy and reduce the intensity of surface damage, resulting in an overall lower wear rate. A typical example of such tribo-oxides is NbO and Nb_2O_5, that form in TiAlCrN/NbN coatings under severe cutting conditions [46,47].

C. Tribo-oxides that transform into a liquid phase at high operating temperatures.

One such example is B_2O_3, which transforms into a liquid phase at temperatures above 350 °C. These tribo-oxides are very effective at machining of Ti alloys [49,50] under roughing conditions at a low cutting speed. Such conditions are accompanied by an intense formation of buildups. The supply of tribo-oxides acting as a liquid lubricant (B_2O_3) can significantly reduce the intensity of buildup formation and substantially improve tool life [50].

Other examples of high-temperature liquid lubricants are V_2O_5 and MoO_3. The first is generated during the high-speed machining Ti alloys using a cutting tool with an AlTiN/VN multilayer coating. The second one (MoO_3) forms during the machining of Inconels by a cutting tool with an AlTiN/MoN multilayer coating [47]. The formation of these oxides results in a strongly improved coating performance due to their mitigation of BUE formation, which is one of the major failure mechanisms of the machining of the outlined alloys.

D. Mixed action tribo-oxides (thermal barrier/lubricating).

Cr-O tribo-oxides possess both lubricating [44] and thermal barrier properties [48]. These tribo-oxides form during the machining of Ti by cutting tools with a CrN coating [49–51].

The second type of mixed-action tribo-oxides is Si-O-based. Silicon oxides have beneficial high-temperature lubricating characteristics [52–56]. The formation of SiO_2 tribo-oxides also enhances heat transfer and reduces the coefficient of friction [52]. Si oxide formation could also improve the surface layer's oxidation resistance [51], nearly doubling the tool life [54].

E. Thermal barriers.

An important category of tribo-oxides containing thermal barrier ceramic phases forms under the severe tribological conditions of high-performance machining [2,8]. These tribo-oxides include Al_2O_3 sapphires, $Al_6Si_2O_{13}$ mullites, $Y_3Al_5O_{12}$ garnets, and $AlCrO_x$ rubies [6,57]. The thicknesses of the tribofilms which form on the surface of the tool during the cutting of hard-to-machine materials fall within nanoscale ranges [28]. These tribo-oxides exhibit a highly beneficial effect on wear performance [28].

The structure of these tribofilms periodically varies from an amorphous to a crystalline one throughout the progress of wear [8]. They may exhibit super-plasticity in an amorphous-like state [58]. Tribofilms of this type, in conjunction with lubricating oxides such as those of chromium and yttrium [59,60], promote very efficient energy dissipation during friction. Because of this, thermal barrier tribofilms can be viewed as surface spatial structures with temporal behavior [61,62].

The most intensive period of tribofilm formation occurs during the initial running stage under extreme tribological conditions typical of extra high-performance machining. As can be seen in Figure 2c, an intense spike in the cutting force takes place at the very beginning of friction (after only 2 m of cutting). A typical feature of chip generation at the very beginning of cutting is the combination of slip (due to chips flowing along the rake surface of the tool) and stick (due to adhesive interaction at the chip/tool interface) [63,64] phenomena. Stick-slip combination during friction is a typical selforganized critical (SOC) process [5,20]. A SOC process corresponds to a strong growth of entropy. This is when the coating layer exhibits the most intensive adaptive response to severe external stimuli through the generation of tribofilms. As a result of this adaptive response, the greatest amount of wear protective and thermal barrier triboceramics begins to emerge on the friction surface, leading to an immediate cutting force decrease (Figure 3d). This is a direct consequence of a selforganization process achieving a strong decrease in entropy production. As was outlined before, some of these tribofilms are in an amorphous state [8], which also contributes to energy dissipation and selforganization. This is known as the trigger effect [28].

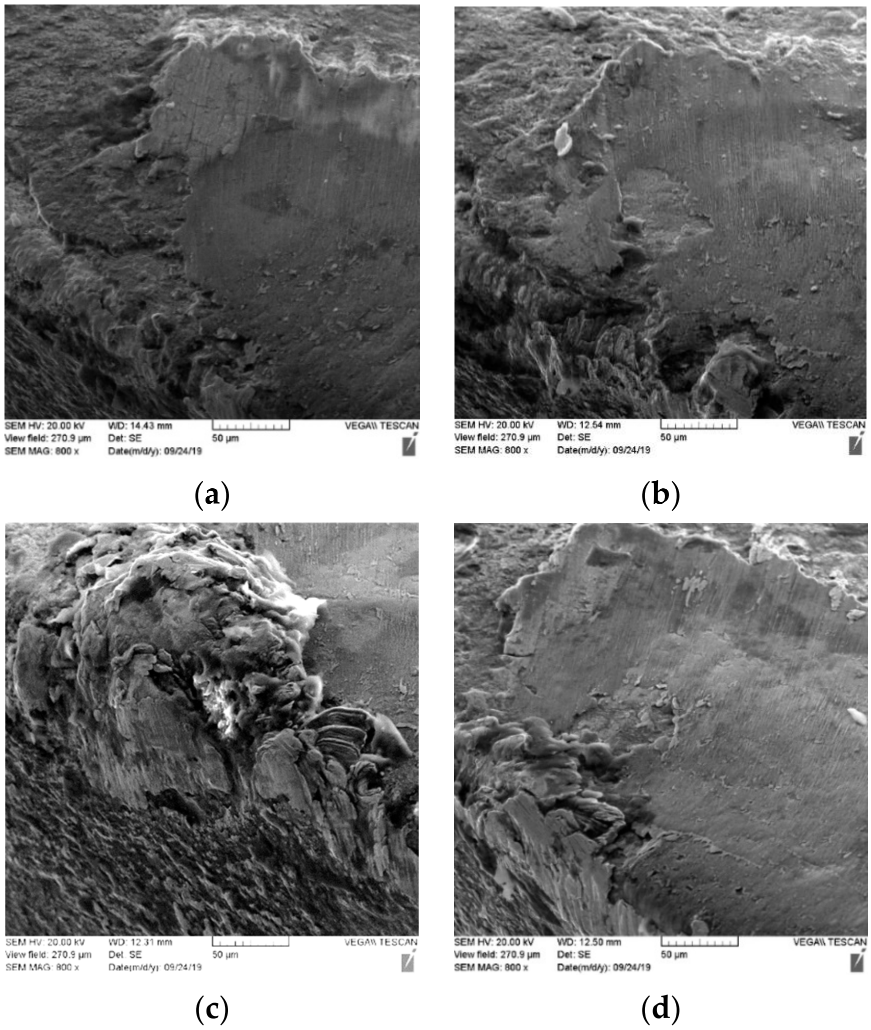


Figure 3. Stages of edge buildup formation during the cutting of SS 304. (**a**) Formation of an adhesive layer at a 200 m length of cut; (**b**) The growth of the adhesive layer at a 400 m length of cut; (**c**) Formation of a BUE at a 600 m length of cut; (**d**) The detachment of the buildup at an 800 m length of cut [18].

Another nanoscale spatial effect could also be brought to attention. It has been indicated in the literature that a greater part of the interactions between frictional bodies is concentrated within the thin layer of the tribofilms [28]. The depth of such a layer is lower by orders of magnitude, which is typically associated with wear and surface damage phenomena [28]. The phenomena involved in this process determine the performance of the tribofilms. Friction periodically generates a very intensive heat flux on the surface. This heat flux is mostly transferred to the external environment due to the very low heat conductivity of the tribo-oxide nanolayer [62–69]. A very strong temperature gradient is thus established under extreme operational conditions, thereby significantly reducing the temperature beneath the thermal barrier and the lubricating nanolayer of the tribofilms [32] and providing excellent protection to the friction surfaces of the entire surface-engineered tribosystem [28].

Based on these outlined characteristics, the thin layers of tribofilms can be said to represent the synergistic, emergent-like behavior of complex matter [4]. The spatiotemporal behavior of the different tribofilms exhibits a high level of synergy [28]. Each of these processes interacts with each other in a complex way with the aim of reducing entropy production during friction. Furthermore, all of the outlined phenomena represent typical features of complex adaptive surface-engineered systems.

An effective thermal barrier property can be provided not only by the aforementioned low thermal conductivity of the tribofilms. A significant part of the friction energy is spent on the processes of dissipative structure formation with negative entropy production. These processes take place within the layer of the tribofilms. As a result, a substantially lower amount of energy is transferred from the tribofilm layer into the cutting tool surface compared with the amount of energy that enters the tribofilm layer from the friction zone.

3.3. Multiscale Selforganization-Based Processes That Occur on the Tool Surface during Cutting

Several multiscale selforganization (SO) [2–4] as well as selforganized critical (SOC) [5] processes take place during cutting. All of these processes develop under catastrophic tribological conditions related to seizure between the contacting bodies [63]. According to the literature [26,27], there are several spots on the rake surface where these processes could be observed. They are the following (Figure 1):

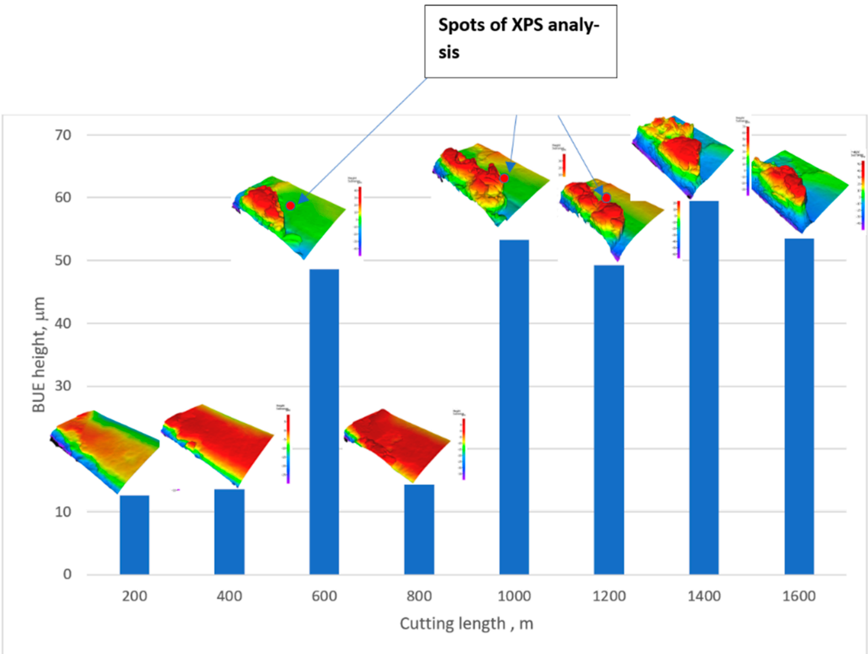
- The tool/chip contact flow zone (zone 1) formed due to sticking accompanied by further shearing and generation of chips as well as adhesive layers on the surface of the tool (a microscale process);
- Zones of intensified seizure (zone 2) with further formation of a BUE within regions of the rake surface closest to the cutting edge (a microscale SOC/SO process).

All of this occurs in tandem with tribo-oxidation and tribofilm formation along the rake surface as well as the surface of the BUE (a nanoscale process).

3.3.1. Adhesive Layers and Edge Buildup

The cutting of hard-to-machine materials under high temperature/stress conditions is accompanied by intensive adhesive interaction at the chip/tool interface, which eventually results in a seizure. It is known from general tribology that seizure is a catastrophic tribological process [2,19]. A tribosystem under seizure may cease relative motion and experience increased adhesive interactions between the bodies in contact [2]. Deformation can become very significant during cutting, in addition to the impact of high temperature. A microscopic volume seizure occurs immediately at the tool/workpiece interface [69], resulting in outlined catastrophic tribological conditions at the tool/chip interface. Modern cutting tool materials are generally strong enough to withstand these catastrophic tribological conditions. However, the relative motion of the contacting bodies (tool/workpiece) during cutting occurs under conditions of seizure across the entire rake surface. This is possible due to the intensive plastic deformation of the workpiece material resulting in its shearing, which takes place within the thin layers closest to the tool/chip interface. These are known as zones of plastic flow [63]. The outlined process of plastic deformation leads to chip generation and the formation of adhesive layers on the surface of the cutting tool (Figure 3).

As previously stated, the SOC and SO processes represent different ways of releasing thermo-mechanical energy that occurs within the tribosystem with respect to wear time (Figure 4).



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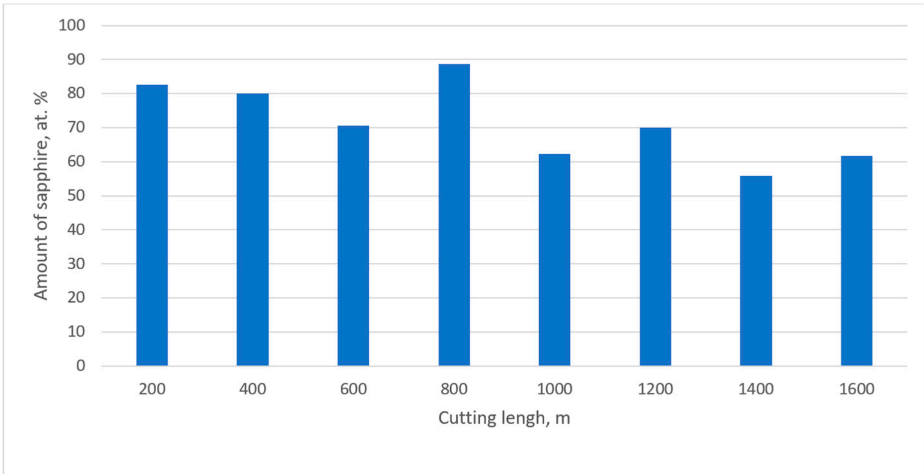


(**b**)

Figure 4. The progression of a buildup edge (BUE) vs. length of cut on the tool in relation to sapphire tribofilm formation on the surface of a CVD-coated tool during the machining of austenitic AISI 304 stainless steel: (**a**) numerical data depicting BUE heights vs. length of cut; (**b**) quantity of tribofilms formed on the friction surface vs. length of cut (XPS data) [18].

During cutting, SOC is the process of energy release caused by the formation of avalanches, i.e., buildups [5]. However, the dissipation of energy through chip generation as well as the formation of adhesive layers and, more importantly, tribofilms, are related to the selforganization (SO) phenomenon [2,3]. For SO to be initiated, the system must not only first lose thermodynamic stability but also undergo an intensive dissipation of energy [2]. A SOC is exactly the kind of process needed for intensive energy dissipation that can trigger SO. Whereas a SOC is inherently associated with the growth of entropy production, in contrast, SO is a process with negative entropy production, i.e., a decrease in the total entropy production of the system. Another significant distinction between SOC and SO is that during the cutting of certain sticky workpiece materials with intense BUE formation, the system will be permanently "tuned" into a state where the SOC process can be repeatedly initiated through an avalanche-like formation of buildups [18]. In an area close to the cutting edge, where thermal-mechanical loading is very high, the SOC corresponds with the intensive interlocking of asperities in the tool/workpiece counter bodies. Therefore, there exists a threshold to stick-slip phenomena by which the bodies in contact cannot move due to intensive seizure. This is directly related to BUE formation [70–72].

BUE formation is also a spatial-temporal process that consists of several stages [21–24]. At the very beginning of cutting, chip generation gives rise to intensive thermo-mechanical processes, which include adhesive interaction at the tool/chip interface and heating and frictional load (see Figure 2) [28]. At this moment, regular deformation patterns (friction-induced stick-slip waves), which emerge at the tool/chip contact interface, are a direct indication of the selforganized critical (SOC) process (Figure 5) [5,18,20].

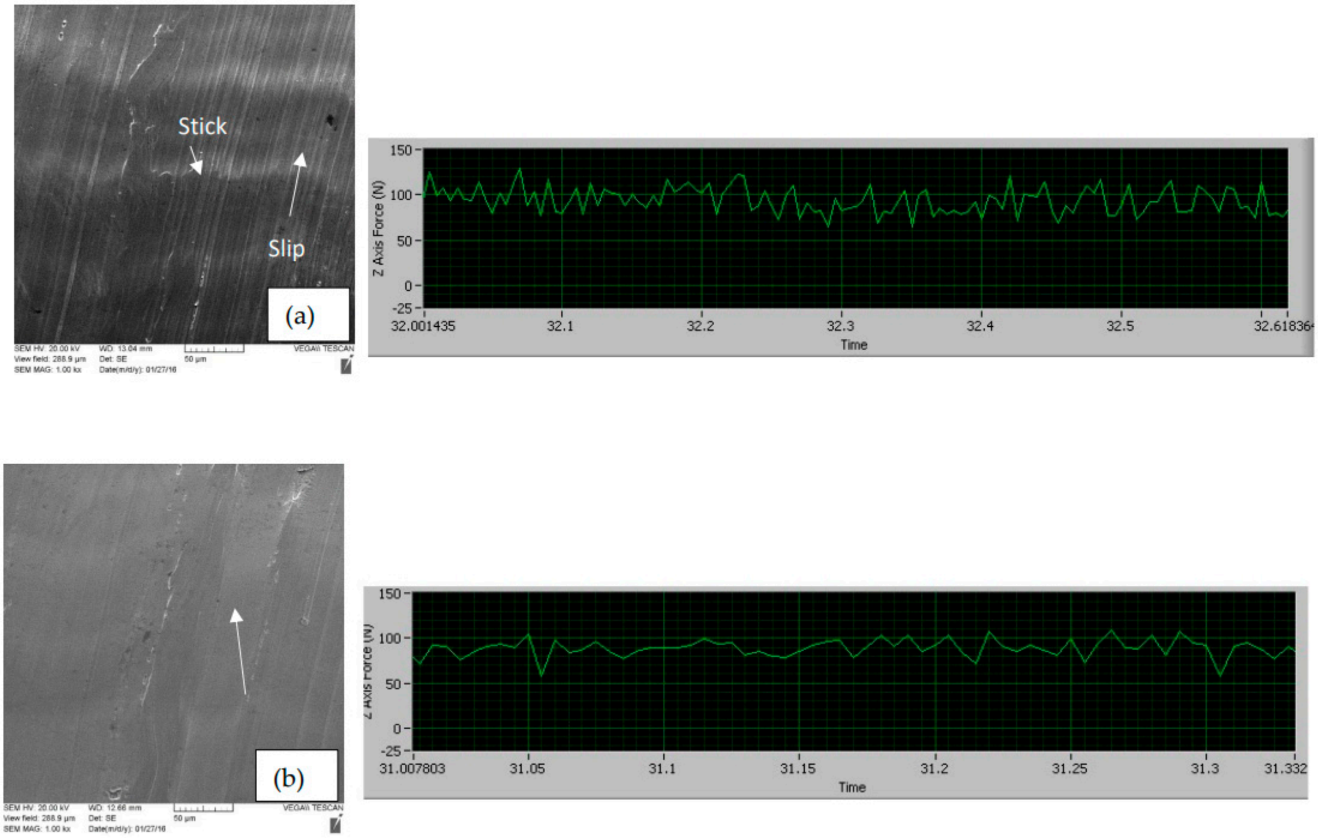


Figure 5. Regular deformation patterns (friction-induced stick-slip waves) formed at the undersurface of the chips generated during machining of SDSS alongside cutting forces data: (**a**) uncoated tool; (**b**) tool with a TiAlCrSiYN/TiAlCrN multilayer coating under optimized machining conditions [28].

Another important process to consider is the formation of multiple initial relatively thin (microscale) adhesive layers stacked on top of one another on the surface of the tool and accompanied by significant plastic deformation (Figure 3a,b). This generates several interconnected structural patterns, such as shear bands, twins, and strain-induced martensite zones, all of which are tightly linked to a selforganization process [9–16]. The interaction and gradual accumulation of initial adhesive layers result in the formation and growth of a BUE in the region close to the cutting edge (Figure 3c) and its further breakage (Figure 3d), which constitute a selforganized critical (SOC) process [18,20,73].

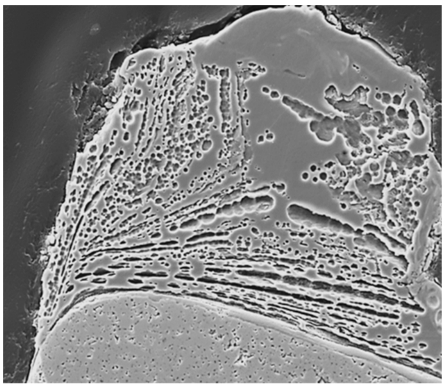
The formation of BUE results in the growth of entropy production [2], which prompts an adaptive response from the surface layer of the tool to external stimuli and directly leads to intensive processes with a positive entropy production, i.e., the amplification of energy dissipation [18]. These processes are spatially and temporarily inter-related in a very complex way [20].

Case studies show [18] that the size of the buildup edge (BUE) tends to fluctuate strongly with respect to wear time.

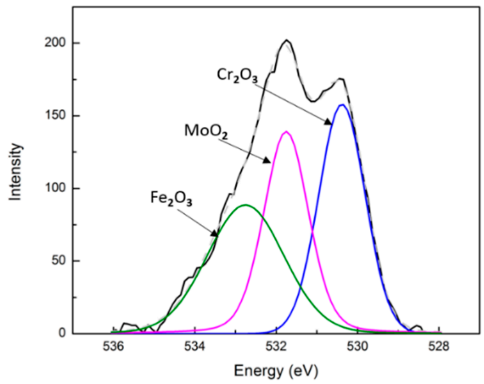
BUE formation during the machining of SS 304 is of particular interest. Figure 4 presents 3D progressive wear studies after each length of the cut interval of 200 m. This corresponds to the SEM data presented in Figure 3. The BUE instability is demonstrated by the periodical volatility of the BUE heights in relation to the previous passes (Figure 4a). XPS studies of the surface in close proximity to the buildup were performed after a similar length of cut of 200 m. Typical XPS results of the corresponding wear regions are presented in Figure 4b. In the initial state, only the corundum (Al_2O_3) phase is present on the surface of the CVD-coated tool [18]. During wear, the sapphire tribophase begins to form at the nanoscale level in the corresponding wear regions.

It is interesting to note that the quantity of sapphire tribofilms that form on the surface of the ceramic coating exhibits the opposite trend to BUE formation with respect to the length of cut (Figure 4b). The formation of these tribofilms follows an unstable pattern, alternating between peaks and troughs in contrast with the BUE height. It can be concluded that a decrease in the number of sapphire tribofilms corresponds to a decrease in the thermomechanical loads on the tribofilm layer. As a consequence, the formation of a buildup layer acquires a portion of the surface protective functions, thereby alleviating friction conditions experienced by the tribofilms.

The BUE has a sufficiently complex structure and characteristics (Figure 6) to be considered a composite "third body". In general, a BUE consists of layers of workpiece material, significantly hardened as a result of intensive plastic flow during chip and adhesive layer generation. Moreover, the intensity of metal flow from the tool/BUE interface to its outer surface visibly varies. (Figure 4a) [1]. The continuously regenerating outer layers interact with the surrounding environment to form thermal protective (Cr_2O_3)/lubricating (MoO_2) tribofilms (Figure 4b).



(**a**)



(**b**)

Figure 6. Buildup cross-section with a visible range of metal flow (**a**) and XPS data of the surface layer of the BUE (**b**). Turning of SDSS [22,23].

As previously stated, a BUE has protective functions [21–23], which can reduce the thermo-mechanical loading on the tool surface [23]. A BUE alters the geometry of the tool. According to [69], a BUE reduces cutting forces and temperatures within the cutting zone. Because a BUE can act as a cutting edge itself, it prevents the tip of the tool from wearing out. The hardness of the buildup tip was reported to be higher than the hardness of the layers close to the tool interface [22]. This is a typical case during the machining of steel [31]. It is also why the BUE is capable of withstanding heavy loads that develop during cutting. However, during the machining of nonferrous material, the hardness of the buildup is similar to the hardness of the original machined material [22,23]. Since the tip of the BUE is severely loaded from its use as a cutting edge, its outer surface could become softened [22,23].

The avalanche-like behavior of buildups needs to be kept in consideration. Repetitive formation and breakage of buildups will eventually result in the catastrophic failure of the entire tribosystem. The application of complex adaptive surface-engineered systems can postpone this catastrophe and therefore extend the tool's operating life. As it is shown in Figure 7, the application of an adaptive coating can strongly decrease the size of the buildups and even transform them into thin adhesive layers, which are the initial stages of BUE formation (Figure 7).

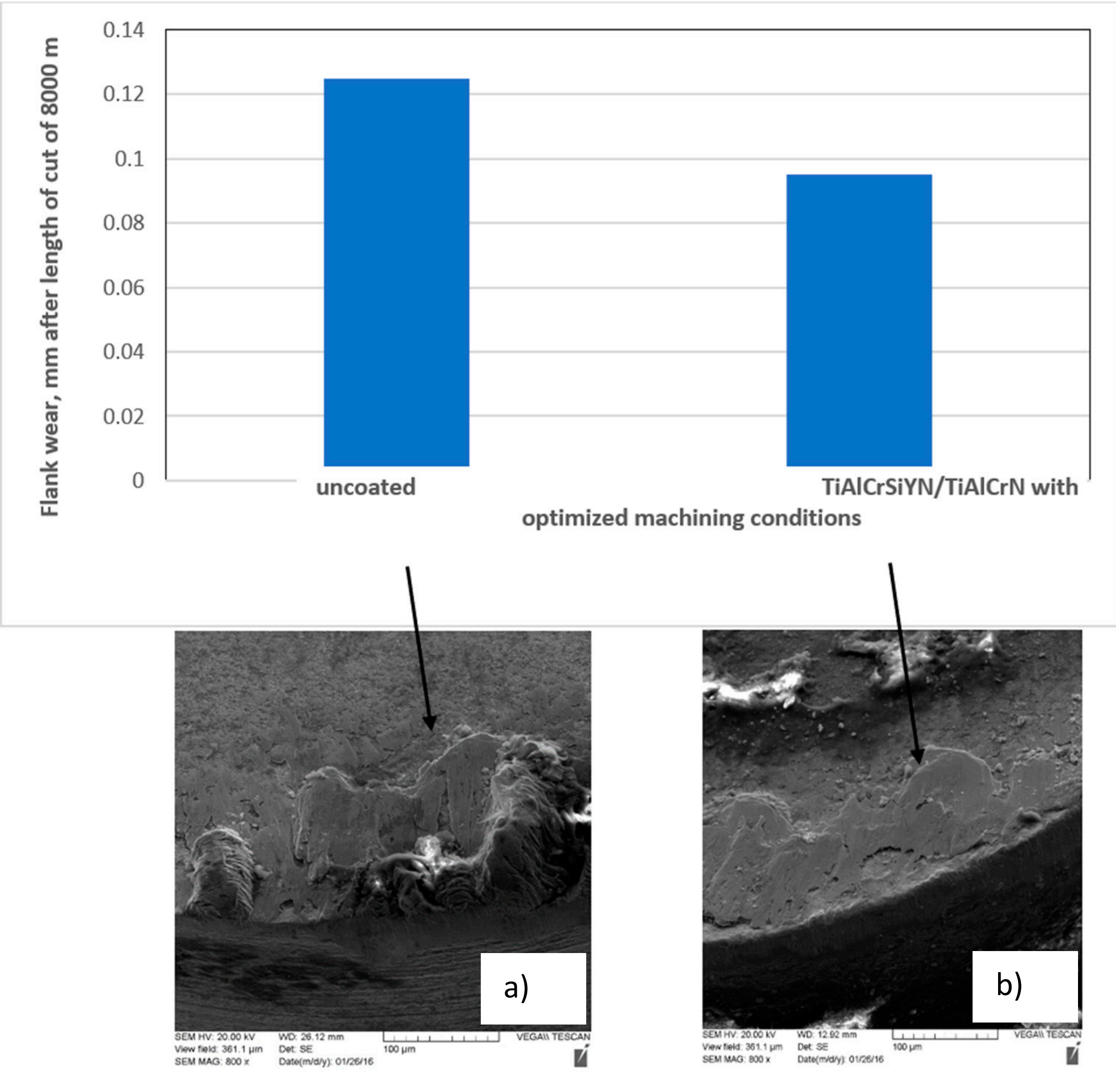
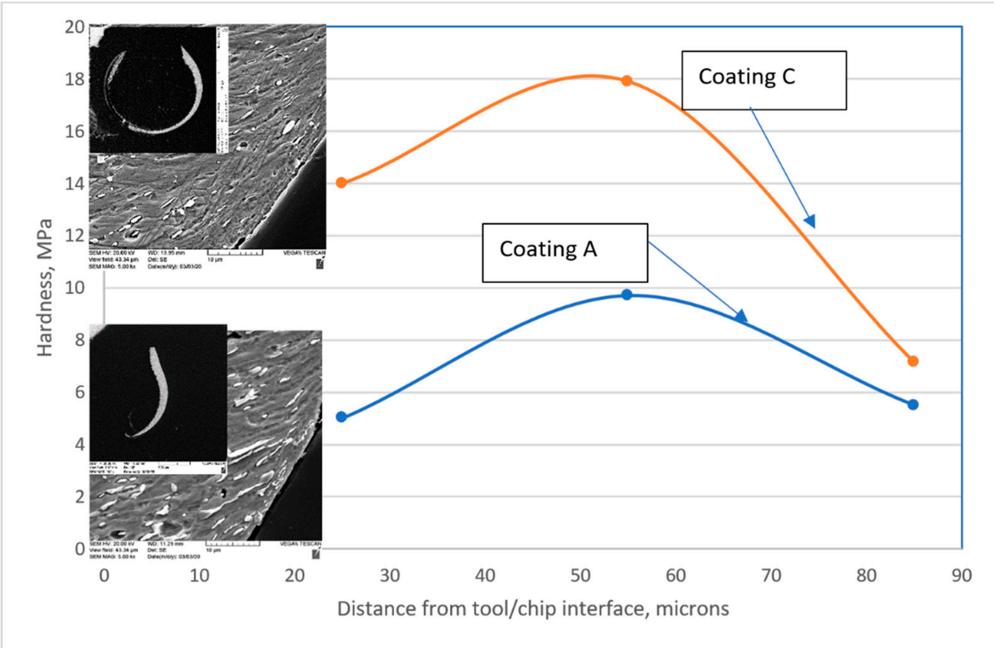


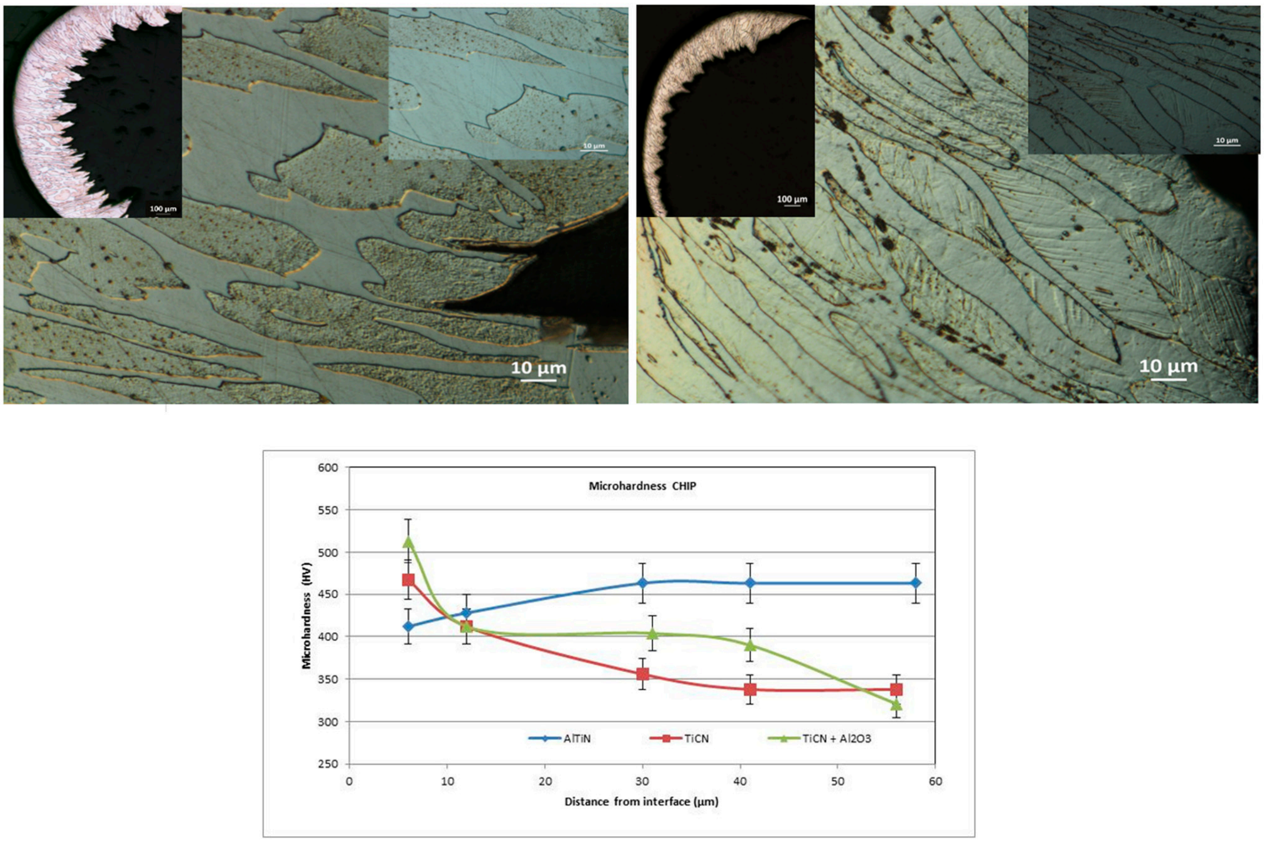
Figure 7. Effect of adaptive PVD coating application on the wear performance (**a**) and intensity of buildup formation (**b**) during the machining of SDSS [28].

3.3.2. Chips

Chips produced during cutting (Figure 8) are excellent fingerprints of the process that takes place at the chip/tool interface.



(**a**)



(**b**)

Figure 8. Formation of strain-induced martensite zones in the chips during the machining of (**a**) Inconel 718 [17]; (**b**) SDSS [74].

The formations of the areas of strain-induced martensite (or twinning) within the sliding zone [9,12–23] of the chips during cutting and within the adhesive layers generated on the surface of the tools are a consequence of selforganization during severe plastic deformation [17]. This, in turn, reduces entropy production [17]. The formation of these zones could cause the hardening of the chips due to simultaneous high-temperature hardening of the workpiece materials (such as Inconels or SDSS [35,74]). In this case, it would result in the formation of curlier chips (Figure 8), less sticking, and longer tool life [35].

4. Complex Adaptive Surface-Engineered Systems Capable of Enhancing Multiscale Selforganization Phenomena during Cutting, Such as the Latest Generation of PVD Coatings

A complex adaptive system is a concept recently introduced in different fields of science [75–78]. Condensed matter, represented by Complex Adaptive Systems, is an upcoming generation of thin-film nanomaterials, specifically hard nano-multilayer PVD coatings designed for extremely harsh frictional conditions. The mechanism of adaptation that arises through a selforganization process with the formation of dissipative structures is characterized by the dynamic regeneration of very thin tribofilms forming as a result of tribochemical reactions on the friction surface [2]. Investigation of the spatial/temporal behavior of these dynamic metastable phases revealed that these unique films possess an atomic-scale (a few atomic layers) thickness [28] and exhibit dynamic behavior in response to the environment [8,32]. The predominant formation of highly protective thermal barrier triboceramics with a sapphire/mullite structure coincides with the establishment of a functional hierarchy within the layer of the tribofilms due to selective adaptation to external stimuli [79]. These superb nanoscale spatial/temporal dynamic structures have a remarkable capacity for soaking energy [28]. The results had also demonstrated that the thermal barrier/lubricating triboceramic films are an integral part of a complex adaptive surface-engineered system in which the underlying coating layer controls the dynamic self-regulative process of tribofilm re-generation [79] and exhibits emergent-like, synergistic behavior [80]. Possessing by design a higher level of complexity and a nonequilibrium state, the coating layer behaves as a high-ordered intelligent tribosystem capable of generating the necessary tribofilms to sustain the extreme external environment with unprecedented efficiency [81].

Highly nonequilibrium, complex-structured thin-film nanomaterials, such as modern nano-multilayer PVD coatings, embedded in a far from equilibrium extreme environment of ultra-speed dry machining of hardened tool steels, demonstrate the full power of the selforganization process [81]. The development of a complex adaptive tribosystem can be achieved by an increase in the amount of alloying elements in the frictional materials, particularly thin-film hard coatings. There exist multiple state-of-the-art PVD coatings that could be considered complex adaptive surface-engineered systems.

One such example of an adaptive PVD coating is the latest generation of TiAlCrSiYN/TiAlCrN bi-nano-multilayered coatings with an improved architecture and micromechanical characteristics which significantly enhance the tool life [82].

High entropy alloy coatings (HEAC) deposited by PVD are of particular importance in this context. As a result of selforganization during the extremely nonequilibrium plasma deposition process, these coatings are capable of developing nanolayered structures in their as-deposited state [6,7]. The nanolaminated structure contributes to crack deflection between the nanolayers exposed to loading, which reduces the probability of coating layer fracture due to improved energy dissipation [7,83]. The ability to dissipate energy under loading is a very important feature of these novel PVD coatings. Multiple micromechanical characteristics of HEAC coatings, such as plasticity index, also known as the microhardness dissipation parameter [2], as well as the hardness to elastic modulus (H/E) ratio, are also indicators of their ability to dissipate energy and thereby reduce its wear damage [84]. The fracture toughness of HAEC coatings is also an indicator of their energy dissipation ability [77–81]. Furthermore, the layer of an as-deposited HEA nano-multilayer coating possesses a nonequilibrium state [77], which greatly increases its probability of undergoing selforganization during friction.

Moreover, in addition to a strongly nonequilibrium state, HEAC coatings contain a high quantity of alloying elements. With the growth in temperature during cutting, a large number of relaxation thermodynamic flows begin to appear, which increases the probability of selforganization and leads to a decrease in the wear intensity. Altogether, this signifies the adaptive performance of HEAC through the formation of beneficial tribofilms on the friction surface that greatly enhances the cutting performance of the coated tool [85–97]. Certain multifunctional boride coatings, in particular HEA borides, are promising for this application as well [93].

A nano-multilayer TiAlCrSiYNTiAlCrN coating with an increased amount of both Si and Y up to 5% [35] could also be considered a HEAC due to its ability to enhance various multiscale selforganization processes during cutting. Moreover, the composition of this coating has been specifically optimized for obtaining the best possible balance of micromechanical characteristics and adaptive performance of the surface-engineered layer. Similar coatings were previously used with success in controlling BUE formation and enhancing the tool life [73].

5. Conclusions

Various multiscale (from the nanoscale up to the micron scale level) selforganization-based processes that occur during cutting are analyzed in this paper. These include the following: (a) selforganization during the process of PVD coating deposition; (b) tribofilm formation with various thermal barrier/lubricating characteristics; (c) chip generation; (d) adhesive layers, and (e) BUE formation on the surface of the tool. Based on the theoretical and experimental analysis, a new strategy of thin-film nanomaterial development is outlined in this study, with the goal of enhancing these various multiscale selforganization processes that take place during cutting. This could be achieved by the application of complex adaptive surface-engineered systems represented by several state-of-the-art PVD nano-multilayer coatings, in particular, HEA PVD coatings and other similar thin-film nanomaterials. A surface-engineered layer primarily affects the process of tribofilm formation (itself a nanoscale selforganization process) on the friction surface. Engineered tribofilms are the most efficient way of addressing the extreme tribological conditions typical of the high-performance machining of hard-to-cut materials. The tribofilms influence the micro- and macroscale selforganization processes related to intensive metal flow at the tool/chip interface, such as the formation of zones of strain-induced martensite within the layer of the chips, the formation of adhesive layers on the rake surface of the tool, and buildups on the cutting edges. Thorough knowledge of these interrelated processes could be of crucial significance in improving the overall wear performance of the cutting tool.

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Abbreviations

SO	Selforganization process
SOC	Selforganized criticality
PVD	Physical vapor deposition
HEAC	High entropy alloy coatings
HREELS	High-resolution electron energy loss spectroscopy
XPS	X-ray photoelectron spectroscopy
BUE	Buildup edge

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