HAL open science

Mini symposium on cutting and machining: 25 years of ESAFORM activity

Domenico Umbrello, Takashi Matsumura, Pedro J. Arrazola, Guenael Germain, Cédric Courbon

To cite this version:

Domenico Umbrello, Takashi Matsumura, Pedro J. Arrazola, Guenael Germain, Cédric Courbon. Mini symposium on cutting and machining: 25 years of ESAFORM activity. International Journal of Material Forming, 2022, 15 (3), 10.1007/s12289-022-01680-w . hal-03684154

HAL Id: hal-03684154

https://hal.science/hal-03684154v1

Submitted on 1 Jun 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

International Journal of Material Forming (2022) 15: 35
https://doi.org/10.1007/s12289-022-01680-w

ESAFORM 25 YEARS ON

Mini symposium on cutting and machining: 25 years of ESAFORM activity

Domenico Umbrello[1] · Takashi Matsumura[2] · Pedro J. Arrazola[3] · Guenael Germain[4] · Cédric Courbon[5]

Received: 19 November 2021 / Accepted: 11 March 2022 / Published online: 7 April 2022
© The Author(s) 2022

Abstract
This paper reports on the state of the art in the experimental and numerical investigations of cutting and machining processes. The contributions on the above-mentioned processes and published on the Proceedings of the European Scientific Association for material FORMing (ESAFORM) Conferences are highlighted. In particular, this literature review is an update of a previous one conducted in the 2007, after ten years of the ESAFORM activities, and it confirms the crucial role played by the minisymposium on Machining and Cutting in this field. In fact, the research has been quite active even in these last fifteen years, as demonstrated by the number of contributions and their relevant scientific contents. As overall, this review shows as the minisymposium on Machining and Cutting, that has been organized since 2001 with no interruptions, has contributed to the scientific progress on the study of the material removal processes.

Keywords Material removal processes · Modeling · ESAFORM

Introduction

Generally, machining operations are material removal processes in which a material is cut to a desired final shape and size. Commonly, turning, shaping, blanking, milling, drilling, grinding and broaching are identified as primary material removal processes although several other advanced machining methods are widely utilized nowadays, such as electric discharge machining (EDM), laser cutting, chemical milling, high-pressure water cutting, electrochemical machining and so on.

It is recognized that material removal processes played a leading role in manufacturing in the history. For instance, it is enough to recall the study carried out by Merchant in 1998 (Merchant 1998) which reported that about 15% of the value of all the mechanical components manufactured worldwide was achieved through machining. This quota surely increased in the last decade due to the growth of the machining market, the demands for micro and nano-machining but also new opportunities to improve the production rate and the introduction of new functional products in several mechanical fields except probably those related the automotive industries (Teti 2002; Dornfeld et al. 2006; Arrazola et al. 2013a; Melkote et al. 2017). In fact, the uncertainty about the future direction of the powertrain is slowly causing turmoil among the traditional engines production stakeholders. In order to deal with this occurrence, they will need to adapt their products/services to the next generation of platforms and expand their portfolio to new and more advantageous market segments. On the manufacturing point of view, although the electrical vehicles (*EVs*) will have less number of components, they will still show the same degree of complexity compared to their Internal Combustion Engine (*ICE*) based competitors. An electric car can be divided into three main components, namely the

✉ Domenico Umbrello
domenico.umbrello@unical.it

1 Department of Mechanical, Energy and Management Engineering, University of Calabria, Arcavacata di Rende (CS), 87036 Rende, Italy

2 Department of Mechanical Engineering, Tokyo Denki University, 5 Senjyu Asahi-cho, Adachi-ku, 120-8551 Tokyo, Japan

3 Faculty of Engineering, Mondragon Unibertsitatea, Loramendi 4, 20500 Arrasate-Mondragón, Spain

4 LAMPA, Arts et Métiers ParisTech, Campus d'Angers, 2 bd du Ronceray, 49035 Angers, France

5 University of Lyon, Ecole Centrale de Lyon - ENISE, LTDS CNRS UMR 5513, 58 Rue Jean Parot, 42000 Saint-Etienne, France

electric motor, a battery pack and a transmission. The battery pack does not have any moving part and the electric energy is obtained from them via chemical processes that aim to power the motor. It transfers power to the wheels through a small transmission (typically a single speed transmission for Tesla vehicles). Consequently, the overall requirements concerning the machining operations of automotive components are extremely lower compared to the *ICE* vehicles production and regard above all the motor and minimally the transmission. Therefore, it is well legitimate to assume that the perused stakeholders will invest their efforts following the direction of the growing up market section that involves machining structured systems. Considering the actual predictions, the most promising sectors that involve machining operations and which are showing substantial growing up trends in the global market are principally those that involves precision machining and hard-to-cut alloys machining.

In particular, the most promising sectors result to be the biomedical industries with the production of higher performances prostheses, aeronautic/aerospace and defense industries concerned by the manufacturing of high-performance alloy components.

Moreover, in the past, manufacturing processes were systematically developed in order to achieve, through innovation, the highest possible efficiency for increasing profit, but, the present trends push manufacturers to develop new methodologies incorporating sustainability concepts (Jegatheesan et al. 2009; Jovane et al. 2008). The traditional practices are being replaced to reduce the energy, materials and other resources required by the processes and the generated wastes from such processes (Jayal et al. 2010; Gutowski et al. 2005). Furthermore, regulations and standards demand even more healthier and safer environments for shop floor workers and employees in manufacturing. For all these reasons and more, a deep analysis of the manufacturing processes performance is needed in order to achieve the most desired manufacturing sustainability practices. Sustainable manufacturing processes are those which demonstrate improved environmental impact and energy-efficiency, generate minimum quantity of wastes, provide operational safety and personal health while maintaining the quality of the products and processes, or even improving them (Lu et al. 2011). In this context, machining is moving through the development of sustainable, or at least lower impacting, lubri-cooling conditions but also an improved control of the machined surface quality and integrity in order to extend the lifetime and in-use properties of a manufactured component.

In addition, during the last decades, a significant enhancement in manufacturing industries has been done by introducing and developing predictive models for machining operations. Machining modeling often targets the prediction of fundamental variables evolution (such as stresses, strains, strain-rates, temperatures, etc.), on varying the process conditions and parameters. However, in order to be useful to industries, these variables must be related to performance measures: product quality (accuracy, dimensional tolerances, etc.), general surface and subsurface integrity, tool-wear, chip-form/breakability, burr formation, machine stability, etc. (Fig. 1). The adoption of machining models by industries critically depends on the capability of a model to correctly pose these links and to predict machining variables and performances (Arrazola et al. 2013a).

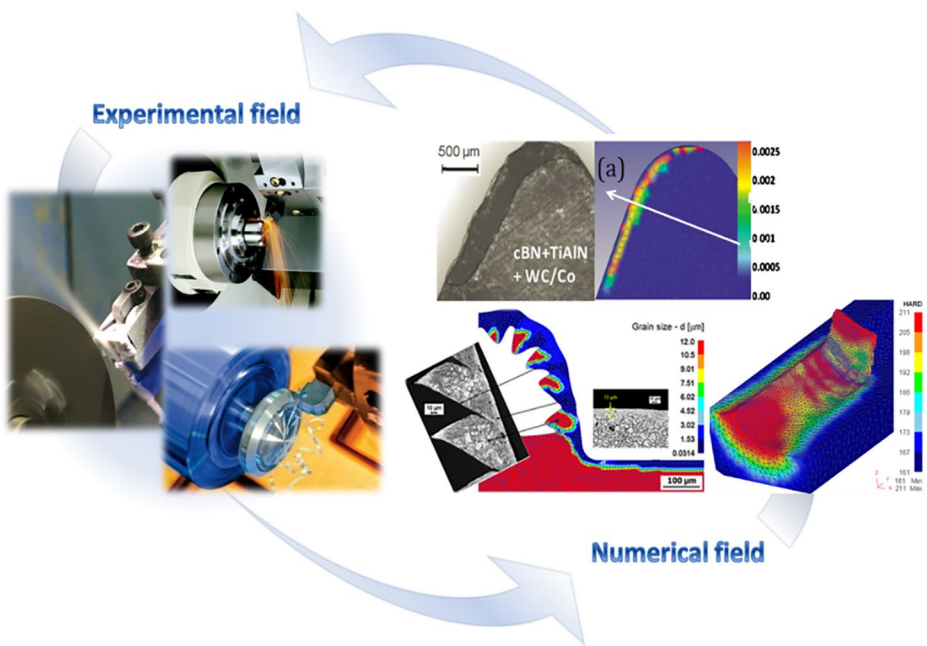

Fig. 1 Finite elements output results used by industries to predict the machining performance experimentally evaluated (Arrazola et al. 2013a)

In this context, also the ESAFORM Community have provided an important contribution to improve the knowledge on material removal processes in the last twenty-five years. The former proposal of a minisymposium on Machining and Cutting Modelling at the ESAFORM Conference in Liege (2001) and its development with no interruptions at all the following editions, paved the way to an important forum where innovative and high-quality researches have been presented.

In this paper a wide bibliography of the papers published in the period 1998–2021 in ESAFORM Conferences Proceedings dealing with the experimental and numerical analysis of the material removal processes are reported. It is interesting to highlight that in these twenty-five years, more than 350 papers focused on material removal processes and selected for the minisymposium on Machining and Cutting have been accepted, presented at the ESAFORM Conferences and published in the Conferences Proceedings. It is important to underline that only a brief remark will be done for the period 1998–2006 since Lorong et al. in 2007 published their review on the first ten years of ESAFORM activities in the fields of machining and cutting. In this period of time, more 80 papers were discussed in their review.

The attention of researches all over the world to publish their research on machining and cutting within the ESAFORM Conferences have been drastically increased in the last fifteen years, as shown in Table 1. In fact, more than 270 papers have been accepted in the period 2007–2021 within the minisymposium on Machining and Cutting and published in the Conferences Proceedings.

Therefore, in order to update the previous review from Lorong et al. in the 2007 (Lorong et al. 2007), the contributions have been grouped in two categories, a first short one referring to the macroscopic approaches and a second one presenting a more detailed contents on those carrying out a mesoscopic analysis.

Table 1 Papers on material removal processes accepted in the last fifteen Editions

Edition	Venue	Nation	Number of accepted papers
10th	Zaragoza	Spain	17
11th	Lyon	France	21
12th	Twente	Netherlands	6
13th	Brescia	Italy	26
14th	Belfast	United Kingdom	20
15th	Erlangen	Germany	19
16th	Aveiro	Portugal	17
17th	Espoo	Finland	19
18th	Graz	Austria	16
19th	Nantes	France	16
20th	Dublin	Ireland	11
21th	Palermo	Italy	27
22th	Vitoria-Gasteiz	Spain	24
23th	Cottbus	Germany	12
24th	Liège	Belgium	19

Brief remarks of MS on machining and cutting activities during the first ten years for Esaform

Lorong et al. (2007) have conducted their review on the first ten years of ESAFORM activities on machining and cutting paying more attention to the enhancements of modeling of material removal processes in both macroscopic and mesoscopic scales.

As far as the macroscopic scale is concerned in those years, the main goals of machining modeling were to predict the behavior of the Workpiece Tool Machine (WTM) system during machining. Within ESAFORM Conferences more than forty papers dealing with macroscopic aspects were accepted and presented. In particular, most of the papers were focused on prediction and modeling of cutting forces and geometrical aspects, some on workpiece deformation, time domain and machine behavior, while very few on frequency domain. The overall data is reported in a summary table in their review (Lorong et al. 2007). The main conclusion at this scale was that it was not possible to accurately simulate the material removal processes due to poor representative mechanical models. Only models for cutting forces and, sometimes, for dynamic issues, seemed to be consistent. They finally suggested that one way to solve the encountered difficulties was to identify models able to couple the analyses at macroscopic and mesoscopic scales.

In contrast, in those years other research works focused on the mesoscopic scale with the idea to propose accurate material modeling, to predict mechanical variables or even thermal variables. It has been a very ambitious enhancement for the machining modeling, since simulation results were at that time mainly limited to the prediction of the cutting forces and to the analysis of simple machining processes under heavy hypotheses. Within ESAFORM Conferences more than 65 papers deal with above mentioned mesoscopic outputs were accepted and presented. In particular, most of the papers were focused on the prediction and modeling of mechanical aspects, chip formation and thermal variables, some on tool wear and few on surface integrity. The overall data is also reported in a summary table in their review (Lorong et al. 2007). The main conclusion at this scale was that huge enhancements were achieved in few years and a positive trend for the future could be expected since modeling of machining operations surely represented a key issue for the developments of such technologies.

Processes and materials investigated and enhancements in macroscopic model

Among all the published papers in the last fifteen years of the ESAFORM conference, the orthogonal cutting (2D) seems to be one of the most studied operation (Bordin et al. 2015), which is close to broaching but still far from other industrial needs in 3D machining. The machining operations more deeply studied in 3D are by far turning (Sartori et al. 2015), drilling (Meena & Mansori, 2016) and milling (Klocke et al. 2018a, b). Broaching (Arrieta et al. 2017) and blanking (of sheet metal), Laser Assisted Machining (Germain et al. 2008), micro milling are additional machining operations that are studied. Table 2 reports a summary of the investigated material removal processes and the relative number of papers in these last fifteen years.

Most of the research in 2D/orthogonal cutting has the aim of gaining basic understanding about the process and to assess the impact of a specific input parameters, such as the workpiece material behavior and tool-chip contact friction, on the key process outputs. The second goal is then to obtain the more suitable laws that allow matching modelling results to experimental ones with regards to cutting forces, temperatures, chip thickness and morphology, etc. Interestingly, several works have been published aiming to predict tool wear, surface integrity (residual stresses, material affected layer, etc.) and even machinability, aspects that are clearly closer to the industrial needs. For 3D machining operations, again, aspects such as cutting forces, temperatures, tool wear, surface integrity (residual stresses, material affected layer, etc.) and process stability have been the major topics. With regards to materials, steels are by far the most studied (Makhfi et al. 2011, Marouvo et al. 2021), followed by Ti alloys, Ni-based alloys (Inconel 718, Waspalloy) and composites.

Table 2 Material removal processes investigated in the last fifteen years within ESAFORM conferences

Machining operation	Number of papers
Cutting (2D and 3D turning)	124
Milling	56
Drilling	24
Micromilling-Micromachining	6
Broaching	5
Laser Assisted Machining	5
Burnishing	4
Abrasive processes	3
Others (blanking)	49 (23)

Enhancements in mesoscopic model

As far as the papers proposing a mesoscopic approach are concerned, very relevant enhancements have been registered in the last fifteen years, mainly as regards the reliability and the effectiveness of the obtained results in terms of mechanical and thermal aspects, tool wear and surface integrity. Furthermore, the research activities are showing a strong emphasis on improving the current models and on finding other materials constitutive laws in order to predict the machining variables by improving the reliability and the stability of these models.

Fifteen years ago, simulation results were quite limited whereas today the number of results provided by machining modeling and analysis is considerable. For the sake of comprehensibility the present review of the mesoscopic models is divided into the following parts:

- Machinability and workability of severe plastic deformation processes;
- Material modelling;
- Prediction of chip formation;
- Prediction of thermal aspects;
- Prediction of tool wear;
- Prediction of surface quality;
- Prediction of surface integrity.

In particular, in the next paragraphs the most relevant enhancements achieved in the last fifteen years will be presented, as well as the new challenges for the years to come.

Machinability and workability of severe plastic deformation processes

Machinability of a material is a critical aspect to determine the machining cost of a component. However, it is not an intrinsic property of the material and it will depend on the final application (tool life, chip breaking, surface roughness, burr formation, etc.) which it is difficult to quantify. The working conditions (cutting parameters, cooling conditions, tool geometry and material) need to be adapted to obtain a minimum tool life, ensuring a proper tool life. For instance, the cutting speed parameter could be modified from ratio values going from 1 to 10, when machining Titanium and Ni-based alloys or Aluminium alloys, respectively. However, although several improvements have been made in the procedure to determine the adequate working conditions, to date in many cases the selection of the working conditions is based on the trial and error approach, which is still far from being the adequate one (Jawahir and Balaji 2000).

Most of the papers dealing with machinability, focus the analysis in fundamental outputs such as cutting forces and

temperatures in orthogonal cutting. Other research works were focused on the characterization of wear such as David et al. (2021) which determined the wear modes in orthogonal milling of 15-5PH Stainless Steel combined with a numerical methodology, where thermal and mechanical loadings were extracted within the coatings and the substrate.

Quite often machining difficult to cut materials such as Inconel 718 has been one of the main goals of researches trying to find the influence of tool material such as ceramic tools (Rinaldi et al. 2019), Sialon (Agirreurreta et al. 2016) or carbide tools (Germain et al. 2008) in tool life. Cooling systems have been as well analysed by introducing innovative cooling methods such as cryogenic machining (Chaabani et al. 2019) and air jet assisted machining with whisker reinforced ceramic tools (Obikawa and Funai 2013).

Also, Titanium alloys have been the focus of several research works (Ayed et al. 2013), (Ben Boubaker et al. 2018), (Harzallah et al. 2016; Ayed et al. 2013) showed that the high pressure water jet assistance can significantly increase the tool life.

Braham-Bouchnak et al. (2010) demonstrated the effectiveness of high pressure water jet assisted machining on a duplex stainless steel (X2CrNiMo 22 – 5), by increasing the tool life and obtaining a good chip fragmentation. Amaro et al. (2018, 2020) employed a tool with interchangeable inserts of sintered carbides coated with AlTiN to mill a duplex stainless steel with trochoidal strategies. Cutting speed range from 120 to 300 m/min were used and the evaluation of tool deterioration and tool life. It was observed a progressive development of a flank wear and a cumulative cyclic process of localized adhesion of the chip to the cutting edge, followed by chipping, loss of the coating and substrate exposure.

With the advent of Additive Manufacturing new research works have been carried out in last years aiming to analyse their machinability compared to those obtained in traditional manufacturing routes (Imbrogno et al. 2016a), (Imbrogno et al. 2018a), (Tamura and Matsumura 2021, (Saffioti et al. 2021a). For instance, Imbrogno et al. (2018a) developed a FE model to analyse the turning process of DMLS Ti6Al4V in dry conditions. An empirical model was implemented to predict lamellae thickness reduction and hardness modifications, showing satisfactory agreement with experimental tests.

Drobnič et al. (2021) employed a novel approach of lubricated liquid carbon dioxide (LCO_2) for milling martensitic stainless steel and compared results with other lubrication conditions (dry, flood, LCO_2, LCO_2 + MQL). It was observed that conventional flooding machining outperformed LCO_2 and LCO_2 + MQL assisted machining in terms of surface roughness. LCO_2 and LCO_2 + MQL cooling/lubricating strategies significantly reduce the temperature in the cutting zone while dry machining strategy provided the longest tool lifetime.

With regards to aluminium alloys, Asad et al. (2008) conducted their research in aluminium alloy A2024-T351 to comprehend the chip formation according to the variation of feed rate and cutting speed.

Fukumori et al. (2019) have shown that the ultrasonic elliptical vibration cutting (UEVC) is an effective method for ultra-precision machining with diamond tools for ferrous materials due to the formation of protective films in

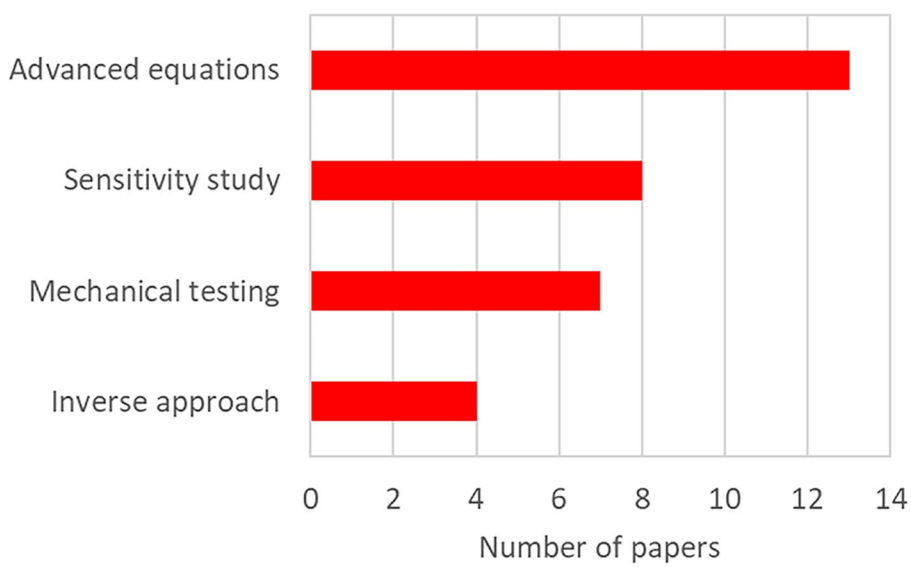

Fig. 2 Papers focusing on material modelling in ESAFORM since 2007

the cutting tools and a reduction in tool temperature. Other authors have analysed the influence of the tool microgeometry in tool life, they observed that among different geometry parameters (clearance angle, rake angle and cutting-edge radius) the cutting edge radius is the most significant factor and it has the maximum influence on tool wear.

Material modelling

Machining is known to be one of the most severe manufacturing processes. Extreme values of strains (1 to 10), strain rates higher than 10^4 s^{-1}, temperatures up to 1000 °C and heating rates close to 10^6 °C.s^{-1} are commonly reported (Chinesta et al. 2008; Courbon et al. 2010). Nevertheless, modelling of machining, and especially metal cutting, has always been of particular interest in order to predict chip formation, forces, strain and temperature fields, tool wear or surface integrity. The performance of any metal cutting model however largely depends on the consistency of the constitutive model employed which thus appears as a key input data.

During the last fifteen years, many research groups within the ESAFORM community have endeavored to improve the knowledge on this input data via more than 30 papers by especially investigating three aspects (Fig. 2): (i) what is the influence of various constitutive equations on the outputs computed by a cutting model, (ii) how to identify the parameters of a given constitutive equation and (iii) how to develop enhanced constitutive equations to improve the performance of a cutting model.

Chip formation is a fundamental aspect in metal cutting and thus was the first output to be investigated. Arrazola et al. (2010) highlighted that the constitutive equation, beside the thermophysical properties, had a significant impact on the serration ratio. On the other side, Shrot and Bäker (2010) showed that, under adiabatic conditions, the chip shape was not drastically modified when 8 different sets of the Johnson and Cook model were implemented. Several works extended such analyses to the comparison of cutting forces, cutting temperature and chip geometry. Jafarian et al. (2014) reported average errors between 10 and 30% on these three outputs compared to the experimental data when cutting Inconel 718, whereas Imbrogno et al. (2014) or Sela et al. (2019) noted an error up to 75% depending on the parameter set when modelling titanium machining. They especially emphasized the importance of the constitutive equation when chip serration occurs, which was later confirmed by several studies (Ducobu et al. 2015; Kugalur-Palanisamy et al. 2021). The machined surface was also investigated and it was found that the subsurface hardness and microstructure were highly dependent on the selected material constitutive model (Rinaldi and Umbrello 2021).

The previously cited works show that a proper identification of the constitutive model is needed to ensure the reliability of the numerical models. A first approach is to perform mechanical testing in order to directly conduct their identification out of the machining process. Shear tests were performed on plates (Ganesan et al. 2008) or hat-shaped specimens (Harzallah et al. 2016) in order to achieve the closest deformation mode compared to the cutting process. In both studies, using a finite-element model of the test itself was required to inversely identify the equation parameters as the loading conditions were finally not that simple to take into account. A simpler method is to conduct uniaxial compression tests such as Courbon et al. (2013) on an AISI 1045 steel, Le Mercier et al. (2014) on a spheroidal graphite iron or Ben Boubaker et al. (2018) on a titanium alloy. While the main benefit of compression tests is to achieve relatively uniform strains up to 100%, a wide range of temperatures could be covered up to 800 °C and strain rates up to 100s^{-1}. However, questions still remain regarding the relevance of the heating and deformation rates applied in these tests compared to those existing in metal cutting. Burns et al. (2010) developed to this end a pulse heated Kolsky bar set-up able to run compression tests at heating rates of up to 6000 ºC s^{-1} and strain rates up to the order of 10^4 s^{-1}. Applied on an AISI 1075 steel, they questioned the potential phase transformation which could occur during the compression tests but which are most probably not taking place in a true cutting configuration. The last trend is to perform more advanced and severe mechanical testing such as the Taylor impact test in order to achieve the most consistent loading configuration (Ducobu et al. 2021).

The intense conditions under which deformation occurs in metal cutting still make the comparison between the observed behavior in conventional testing methods and the one encountered in the process relatively tricky. Therefore, a second approach is to use machining itself to inversely identify constitutive equation. This requires the development of a numerical (Chinesta et al. 2008) or analytical model of the cutting process (Pittalà and Monno 2010) and an inverse procedure to conduct the identification. Some studies defined an objective function based on force components only (Maurel et al. 2007), chip geometry only (Shrot and Bäker 2012) or force components and cutting temperature (Chinesta et al. 2008).

An identification via an inverse method requires first the definition of the targeted constitutive equation, i.e. supposing thus that the way the material behaves is already known. Mechanical testing can directly provide stress strain curves on which the formulation of advanced constitutive equations can be proposed. The trend over the last decade is to develop new constitutive models including not only strains, strain rates and temperatures with constant coefficients but

rather varying ones and material based parameters. Temperature dependent Johnson and Cook parameters were proposed by Harzallah et al. (2016) whereas a plasticity model was combined with a damage model in several studies (Saanouni et al. 2009; Umbrello et al. 2012). Material aspects were included by different approaches such as taking into account the hardness (Umbrello et al. 2007, 2012; Biermann et al. 2010; Tiffe et al. 2014), microstructural evolution due to dynamic recrystallization (Thibaud et al. 2007; Courbon et al. 2013; Le Mercier et al. 2014), dislocation density (Kalhori et al. 2010; Rinaldi et al. 2020) or even recently crystal plasticity (Boubakri et al. 2019).

Finally, the Fig. 3 shows the materials that were mainly investigated. If steels were indeed the most common ones, difficult to machine materials were obviously of high interest such as Nickel, Titanium or stainless steel alloys. This summary confirms that understanding the deformation mechanisms associated with the chip formation can be seen as essential in order to propose advanced constitutive models not only based on empirical fitting but also on a strong physical basis.

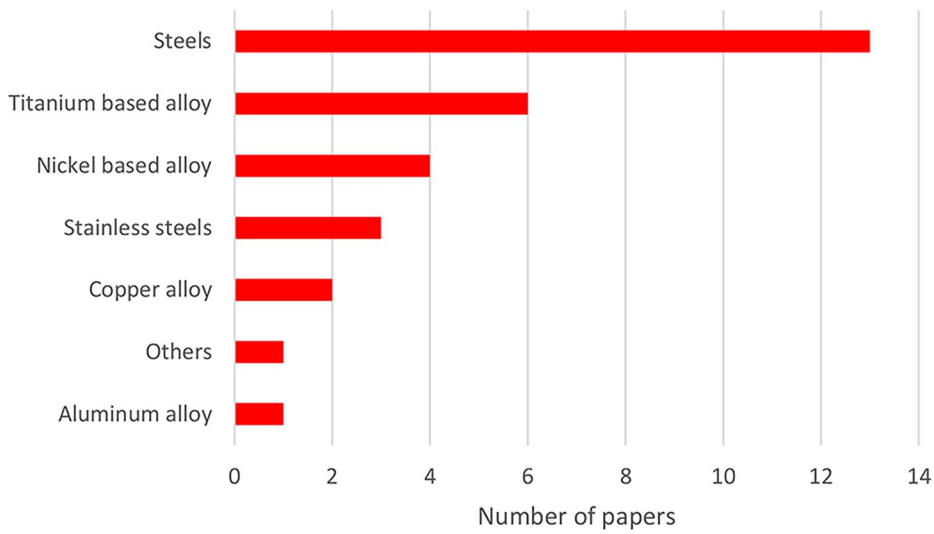

Fig. 3 Materials discussed on material modelling in ESAFORM since 2007

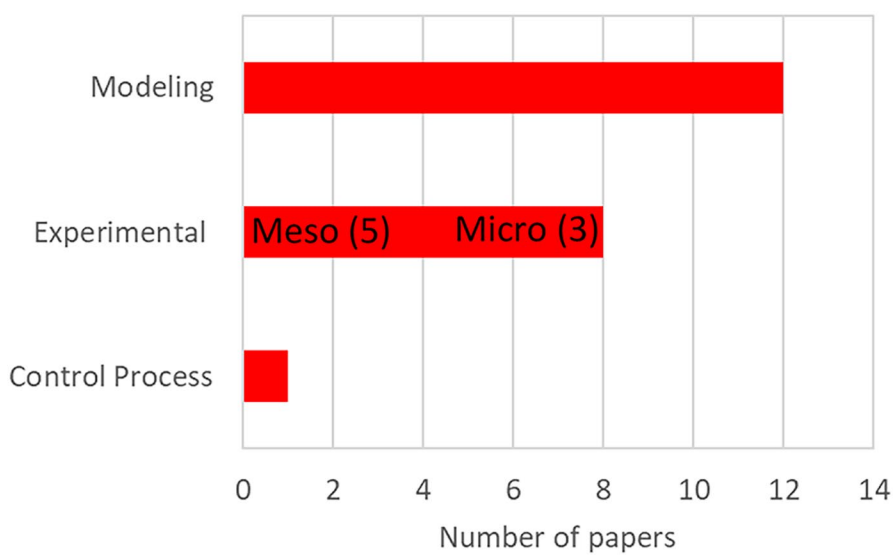

Fig. 4 Papers focusing on chip formation in ESAFORM since 2007

Prediction of chip formation

Understanding chip formation has been of interest to the community for many years, 21 papers have focused on this theme since 2007. This understanding of the phenomena involved is very difficult, because everything happens in a very small area (a few square millimeters) where very strong thermal and mechanical gradients are present. The approach is complex because the thermal and mechanical phenomena are strongly dependent on one another (thermomechanical phenomenon) with strongly nonlinear behaviours. It is therefore difficult to separate the thermal and mechanical phenomena. One way to achieve this is to use assisted machining, by preheating the workpiece with a laser beam (Germain et al. 2008) or by cooling the cutting zone with a cryogenic fluid (Imbrogno et al. 2018b; Chaabani et al. 2019, 2020) which showed the differences in machinability and chip formation with and without assistance.

The experimental approach being very difficult, many works propose a numerical approach, but there are also experimental papers at the scale of the tool (meso), or more finely, at the scale of deformation zones, for the chip formation (micro). The Fig. 4 shows this distribution and all these studies were mainly focused on Titanium alloys and steels as shown in Fig. 5.

A macroscale approach is used to know the chip formation on specific materials, such as Waspaloy, nickel-based superalloys (Caruso et al. 2017), a fine grain steel (Komatsu et al. 2011) or additive manufacturing martensitic stainless steel (Tamura and Matsumura 2021), but also for particular machining operations, such as the use of very low feeds, $f < 0.025$ mm / rev (Chodor et al. 2018). These studies are similar to observing the machinability of materials.

For a more detailed understanding of the phenomena, orthogonal cutting machining is used. Some works have used an experimental approach by fast cameras to observe the zones of chip formation (Batista et al. 2012). This experimental approach is very interesting (and is currently developing), but only the surface of the material can be observed. The internal deformation and thermal quantities are not visible. On the other hand, the numerical simulation makes it possible to know these internal values in the various zones of chip formation.

The numerical approach makes it possible to calculate all the local quantities, but its implementation is not easy. The results obtained depend a lot on modeling. Asad et al. (2008) showed that it is important to have a law of plasticity and a law of damage relevant to properly model the behavior of the material. The numerical approach makes it possible to calculate all the local quantities, but its implementation is not easy. The results obtained depend a lot on modeling. They also showed that it is important to have a law of plasticity and a law of damage, relevant to properly model the behavior of the material. Numerous studies have therefore been carried out on the constitutive laws of materials in high strain for very high strain rates and for high temperatures (Ducobu et al. 2015; Kugalur-Palanisamy et al. 2019, 2020). These studies are carried out for metallic materials, but can be adapted to the behavior of composite materials (Benhassine et al. 2018). Numerical simulations must imperatively be validated by a comparison with experimental results, as shown by Asad et al. (2008), Haddag et al. (2016) and Benhassine et al. (2019). By numerical

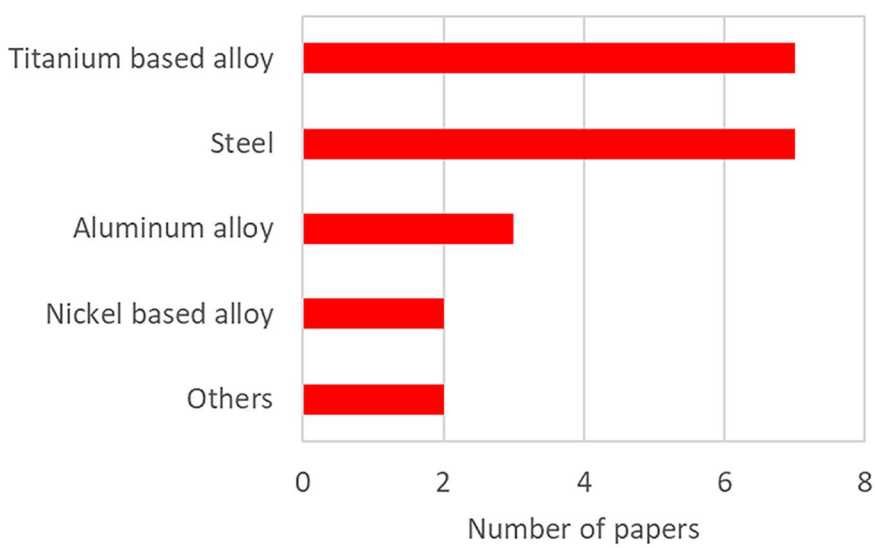

Fig. 5 Materials discussed on chip formation in ESAFORM since 2007

simulations, Arrazola et al. (2010) showed that the self-heating and thermal softening parameters were very influential parameters on chip segmentation. These models are important for the understanding of the phenomena, but must also be adapted to the processes to improve the computing time for example (Fabre et al. 2016).

Prediction of thermal aspects

The prediction of the thermal aspects is surely the most critical point, because the measurements are very difficult to carry out, and the modeling complex, their knowledge is therefore very complicated, while the effect of the thermal aspects is very important in machining operation. In fact, the temperatures will influence: (i) the behavior of the material, and therefore the cutting force (ii) the wear of the tool which increases with the rise in temperature (iii) the surface integrity, in particular the residual stresses which will influence the in-service behavior of the machined part.

Due to the complexity of temperature measurements, an analytical approach (Matsumura et al. 2008), finite difference method (Matsumura et al. 2010) or finite element

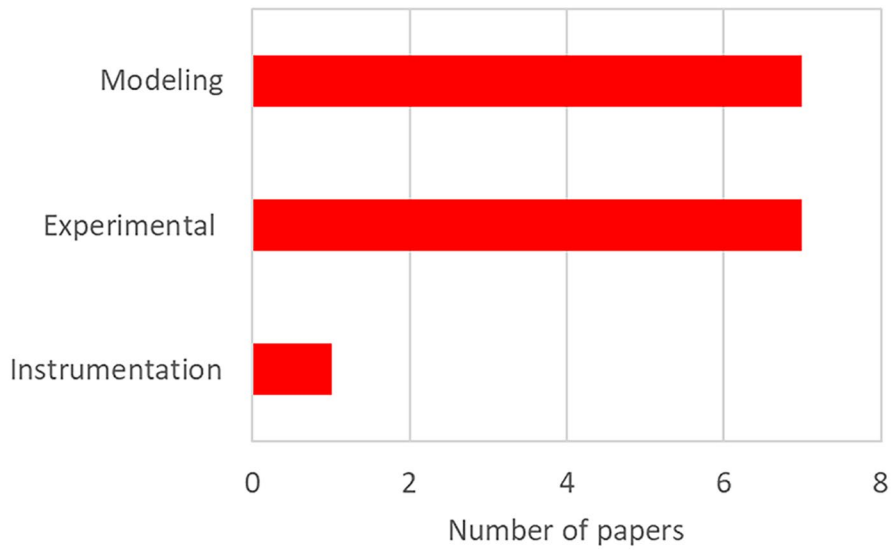

Fig. 6 Papers focusing on thermal aspects in ESAFORM since 2007

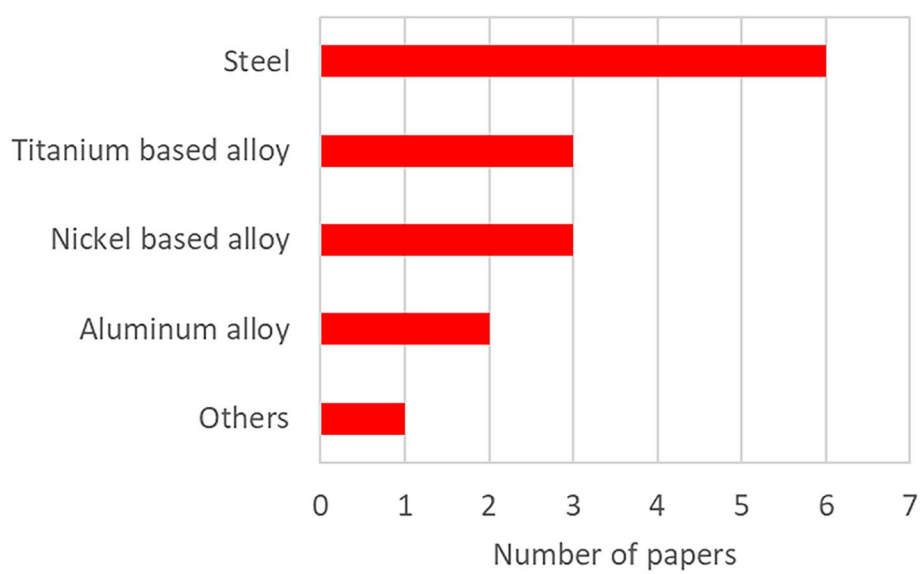

Fig. 7 Materials discussed on chip formation in ESAFORM since 2007

method (Filice et al. 2007; Arrazola et al. 2013b) can be used to estimate the temperatures reached in machining. Figure 6 shows this distribution and all these studies focused mainly on steels and not ferrous alloys as shown in Fig. 7.

An experimental approach can also be proposed, with the use of a calorimeter (Denkena et al. 2012), the use of thermocouples in the workpiece (Drobnič et al. 2021) or by infrared cameras (Ferreira et al. 2014; Caruso et al. 2017). These approaches can be complementary, in particular the use of finite element calculations and infrared camera measurement to show the effect of the machined material (Careri et al., 2020; Montoya et al., 2014), of the cutting tool (He et al. 2013) or of the cutting parameters (Angiuli et al. 2019) on the temperatures reached. These studies remain very global (macro scale), but recent works, such as (Bonnet et al. 2021), allow a more local approach with an estimation of the temperature fields in the cutting zone.

Prediction of tool wear

Fifty-four papers focusing on tool wear have been presented in ESAFORM since 2007. These papers are classified into (1) wear characteristics; (2) wear modelling and simulation;

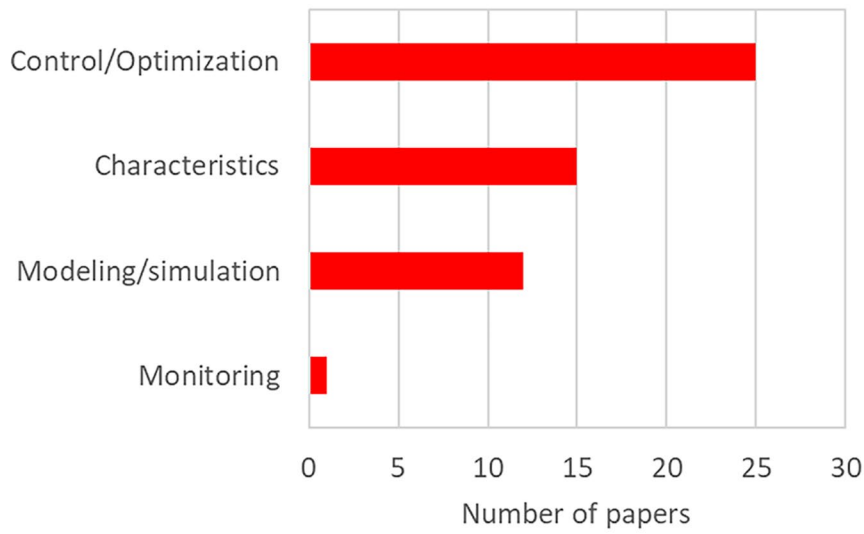

Fig. 8 Papers focusing on tool wear presented in ESAFORM since 2007

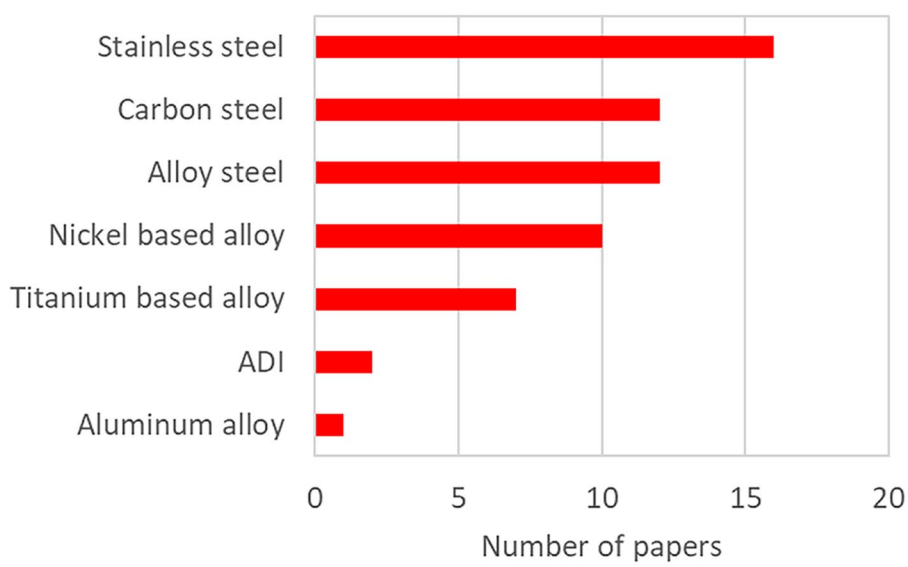

Fig. 9 Materials discussed in ESAFORM since 2007

(3) wear control and optimization; and (4) wear monitoring. The numbers of papers are shown in Fig. 8.

Many papers related to wear characteristics discussed the wear progresses and the tool damages in nickel based alloys such as Inconel, stainless steels, alloy steel, titanium alloys (Ti6Al4V), carbon steel, ADI, Waspaloy, and aluminum alloy as shown in Fig. 9.

The materials made by additive manufacturing have recently investigated. The tool wear of a titanium alloy made in EBM (Electron Beam Melting) was discussed with a wrought one (Bordin et al. 2014). The cutting performances were discussed with the coating, the tool treatments and the tool material. The tool life largely depends on the hardness of the material. The tool wear in cutting of Inconel with a SiAlON tool was investigated in manner of circular ramping (Agirreurreta et al. 2016). Whisker reinforced ceramic tool was tried to machine Inconel assisted by air jet supply in turning (Obikawa and Funai 2013).

Regarding the wear modelling and simulation, tool wear progresses have been simulated in FEM, analytical and experimental models. Height papers simulated the tool wear in FEM. Analytical models were applied to tool wear prediction in two papers. A paper presented an experimental model with ANOVA (Mehrban et al., 2008). Many studies have simulated in turning, milling and drilling of carbon steel as a widely machined material.

The wear control has been studied in terms of the cutting temperature because the tool wear depends on the temperature on the rake and the flank faces. The strategies in the reduction of the temperature are: (1) cryogenic coolant supply; (2) high pressure cooling system; (3) improvement of tool surface treatment; and (4) path control.

Four papers discussed the effect of cryogenic cooling on the tool wear with comparing to the conventional coolant supply. The effect of the cryogenic cooling has been confirmed in cutting of difficult-to-cut material such as Inconel (Chaabani et al. 2019), hardened AISI 52,100 bearing steel (Umbrello et al. 2011b) and titanium alloy, Ti6Al4V (Tirelli et al. 2014). An economical assessment of the cryogenic cooling was done with optimizing the cutting conditions (Tirelli et al. 2015).

High pressure coolant system has been studied to improve coolant supply. Because the space between the tool and the workpiece or the chip is narrow, the coolant cannot achieve the tool tip easily. Therefore, the supply pressure of the coolant is a critical factor to control the tool wear with the temperature. The high-pressure coolant supply is also effective in the chip breaking/fragmentation. The chip formation changes at higher than 250 bar and the tool wear reduces with the cutting force (Braham-Bouchnak et al., 2010). The dominant wear mechanism changes with pressure of the coolant supply (Ayed et al. 2013). The tool damages were well investigated with the chip fragmentation when the pressure of the coolant supply increases. Then, the tool temperature and the manufacturing cost were associated with the diameter of the coolant nozzle (Klocke et al. 2013).

The tool treatment is an interesting strategy to control the temperature on the tool face. In cryogenic treatment, the tool material is held for a long time at temperatures of subzero range; and is returning to the room temperature. The treatment changes mechanical properties and the crystal structure of materials and improves the tool wear resistance (Thamizhmanii and Hasan 2012). As another approach, micro textures were fabricated on the tool faces to promote the coolant supply effect and reduced the temperature with a jet coolant (Obikawa et al. 2018). A triangular groove was also fabricated on the flank face and the coolant flow was analyzes using Particleworks, one of codes for smoothed particle hydrodynamics (Obikawa et al. 2019).

Regarding the path control, the cutter is controlled to reduce the tool-workpiece contact and the temperature rise in milling. In the trochoidal tool path for slotting, heat and wear were distributed evenly, providing a longer tool life than traditional milling (Amaro et al. 2018, 2020). Tool engagement is also a factor influencing on the tool wear. The flank wear was investigated with changing the engagement angle and a feasibility map was made for the depths of cuts and the engagement angles (Del Prete et al. 2012).

Tool wear monitoring has recently become more popular with demands of the intelligent machining. The tool wear and the tool breakage are critical in continuous production. A new approach was presented using standard transducers available on actual machines for a monitoring of cutting process. The presented method analyses instantaneous variations in rotational frequency to observe milling operation (Girardin et al. 2010).

Regarding the tool wear modeling and simulation, it is well known that it is classified into diffusion, adhesion and abrasive in metal cutting. In the diffusion wear, parts of compositions in the chip and the tool replaced each other under high temperature. In cutting of carbon steel with cemented carbide, cobalt working as binder diffuses into the chip. Then, particles of tungsten carbide are taken out with the chip flow. In the diffusion wear model, the wear rate is associated with the activation energy, the gas constant and the local temperature measured as the absolute temperature (Takeyama and Murata 1963).

The adhesion wear is induced by the material adhesion depending on the temperature at the interface between the chip and the tool face. The adhesion wear model also considers the material removal with the asperity contact associated with the material hardness. The adhesion, therefore, is controlled by the stress on the tool face and Holm's probability, the probability of generation of the wear particles

at a contact. The Holm's probability is formalized with the activation energy depending on the surface structure and the temperature at the interface. The adhesion wear rate is associated with the stress and the temperature on the tool face (Usui et al. 1984).

The abrasive wear is caused by ploughing, mechanical removal in subsurface of the tool. In the ploughing model (Rabinowicz et al. 1961), the wear volume is characterized by the normal stress and the material hardness depending on the temperature. The abrasive wear rate is determined by the stress and the temperature on the tool face (Usui et al. 1984).

In the wear models, the wear characteristic constants are required for the tool and the workpiece materials. As an inverse analysis, the wear characteristic constants were identified to minimize the prediction error of the tool wear in the simulation (Matsumura et al. 2008). The wear models were discussed in the flank wear prediction (Umbrello et al. 2008). As another wear model, adhesion, abrasion, and fracture are included with the initial and the fast wear process (Franco et al. 2007).

The tool wear prediction requires the stress and the temperature distributions. In the analytical simulation, the stresses on the rake and the flank faces are given with assuming the distributions. The temperature distribution was simulated in finite volume method (Matsumura et al. 2008).

he stress and the temperature distributions are also obtained numerically in FE analysis. The contact interface conditions are critical in the simulation, which depends on the friction and heat partition conditions. The tool wear prediction was conducted after assessment of the interface definition (Giovenco et al. 2019). The tool wear mechanism of the coating thin film was investigated in detail and a multi-scale numerical model was applied to predict the tool wear of alumina and TiAlN coated tools in orthogonal milling (David et al. 2021). The diffusive wear on the rake face in turning was simulated with the tool mesh updating corresponding to the geometry of the crater wear in 3D FE analysis (Attanasio et al. 2008). Abrasive and diffusive wear models were also applied to the prediction of the crater wear. The areas of the abrasive and the diffusive wear were determined by the temperature distribution on the rake face, which was simulated in 3D FE analysis (Attanasio and Umbrello 2009). The abrasive/diffusive combination model was also applied to flank wear prediction in turning with 3D FE analysis (Attanasio et al. 2011). The increase of the cutting force with the tool wear, which has influence on the machining quality, was simulated in 2D FE analysis (Equeter et al. 2018). As advanced simulation, the tool wear was predicted using a microstructure-based FEM (Sáez-de-Buruaga, 2015).

Prediction of surface quality

Surface integrity has a remarkable influence on aspects such as fatigue life, tribology and corrosion. The surface integrity condition is defined by the surface roughness, residual stresses and material affected layers. The topic has been tackled very often during the last fifteen years of ESAFORM conference within the mini symposium on Machining and Cutting. Analysis of residual stresses has been by far the subjects more analyses for several machining operations (turning, milling, burnishing) and a variety of materials (AISI 52,100 steel, Ti64, Cemented carbides, AISI H13, Duplex stainless steel, copper, etc.) with empirical and modelling approaches. For predicting the complexity of residual stress (Caruso et al. 2010) and material affected layer phenomena (Schulze et al. 2013) (Umbrello et al. 2011a), finite element codes such as Abaqus, Deform, AdvantEdge or Deform are employed.

Gravier et al. (2008) analyzed the electromechanical behavior of the copper machined surface and showed that the most influent cutting parameters are feed rate, lubrication and tool nose radius.

Rech et al. (2008), obtained residual stresses empirically and numerically after belt finishing, showing that it improves very significantly surface integrity by the induction of strong compressive residual stresses in the external layer in samples obtained by hard turning.

Caruso et al. (2010) analyzed residual stresses induced by orthogonal cutting of AISI H13 tool steel using the Finite Element (FE) code of Abaqus and validated the results using X-ray diffraction technique. Finally, the proposed FE model was applied to investigate the influence of flank tool wear and cutting regime parameters on surface residual stresses distribution in the machined surface of AISI H13 tool steel. They concluded that as the cutting speed, uncut chip thickness and tool wear increase surface residual, stresses increase as well, becoming more compressive.

Rizzuti et al. (2010a, b) studied numerically the prediction of residual stresses in the orthogonal cutting process of machining AISI 1045 steel using uncoated WC tool, obtaining a reasonable agreement was obtained between the numerical predicted residual stresses and those experimentally measured.

Desmaison et al. (2011) used Forge® to predict the residual stresses distribution and cutting forces, hat ware validated with experimental tests.

Andreas et al. (2012) analyzed the residual stresses generated in grinning of cemented carbide employed in tooling for forging. It was observed that for equal removal rates, higher hardness of cemented carbides results in higher compressive stresses due to higher required cutting forces. Higher feed values result in lower compressive stresses

caused by thermal effects. Thus it was proposed that in order to achieve high cost effectiveness, a favorable surface quality and high compressive stresses, grinding strategies with low feed and high in-feed values should be preferred.

Umbrello analyzed trough experimental testing the influence of working conditions in surface integrity in Ni-based alloys such as Inconel 718 and Waspaloy (Umbrello 2014). For instance, he concluded that in the case of Waspaloy the wear rate increases with the increasing of both feed rate and cutting speed, surface roughness in machining Waspaloy alloy are comparable with those obtained by grinding process and that the grain size on the machined surface cannot be revealed by an optical microscope even when the largest magnification was used and XRD observations highlighted that there is a phase change on the machined surface for tests carried out at 70 m/min. Similar observations were found for Inconel 718 (Umbrello et al. 2012). However, the appearance of the featureless layers formed under machining underlined that significant grain refinement occurred due to dynamic recrystallization and XRD observations highlighted that there is a phase change on the machined surface for several tests.

Klocke et al. (2018a, b) observed that when machining AISI 304 steel, the resulting microstructure strongly depends on the cooling condition. They concluded that it is possible to achieve a nanocrystalline surface layer in turning when using a cutting tool with a large cutting edge radius under finish cutting conditions and the use of cryogenic coolant. Also, he observed that refined surface layer can enhance properties in terms of the surface hardness only to an extent, but has its downside on the surface quality, where numerous built-up edges were found.

Prediction of surface integrity

In several key industrial sectors, especially concerned by safety-critical components, the quality requirements do not only consist in geometrical specifications but also in the ability to withstand loading conditions in service such as fatigue resistance (Mäntyjärvi et al. 2009), creep or stress corrosion cracking (Gravier et al. 2008). The performance of these high added value components depends to a large extent on the physical state of their surface layer characterized by three particular features: the surface topography, the distribution of residual stresses and the subsurface microstructure induced by the last manufacturing process. Forty papers tackled this topic during the last fifteen years in the ESAFORM machining community, confirming the growing interest not only for academy but also for industry. The Fig. 10 highlights the contributions focused on each surface feature with numerous studies on the microstructural evolution as well as recent strong developments in modelling of surface integrity.

Surface roughness is the most common and easiest to measure surface integrity parameter. If simple geometrical equations exist to estimate the mean surface roughness (R_a) and mean surface roughness depth (R_z), being able to predict them over a wide range of cutting parameters requires some other approaches. Response Surface Methodology (RSM) (Del Prete et al. 2010a) and ANOVA (Saffioti et al. 2021b) were commonly applied to generate empirical models and assess the most influential parameters. In broaching, Makarov et al. (2008) and Arrieta et al. (2017) showed that surface roughness was also highly dependent on the microstructure of the material especially due to the small uncut chip thickness compared to the grain size. Whereas

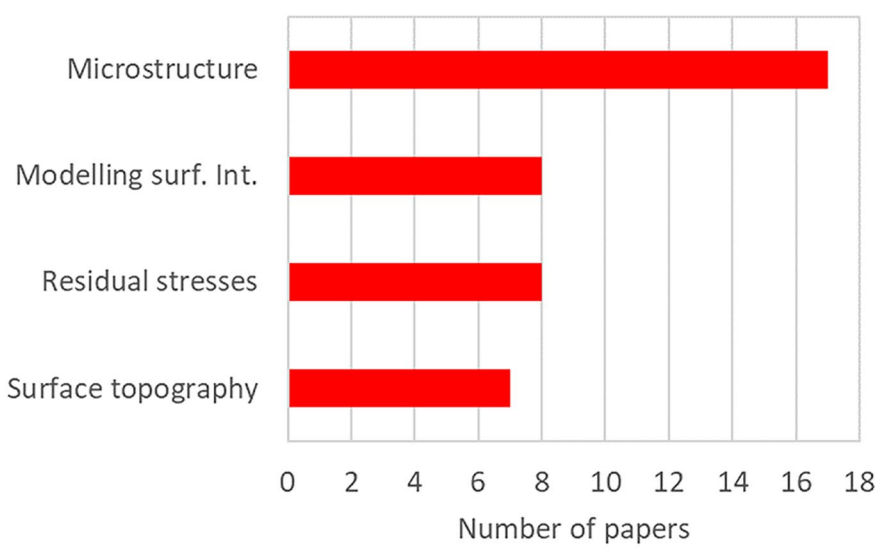

Fig. 10 Papers focusing on surface integrity in ESAFORM since 2007

this parameter is relatively well controlled in general, it may require the use of alternative lubrication methods in machining such as High-Pressure-Jet-Assisted-Machining (HPJAM) when cutting duplex stainless steels (Braham-Bouchnak et al. 2010), cryogenic fluid when cutting titanium alloys (Bellin et al. 2017) or even recently (Bertolini et al. 2021) on ultra-high-molecular weight polyethylene.

Residual stresses remain a key component of the surface integrity as they can at the macro scale lead to critical part distortions (Segurajauregui et al. 2007; Fergani et al. 2016). On a local scale, a residual tensile state can exist (Germain et al. 2008) which may promote the formation and propagation of cracks, drastically affecting the fatigue resistance of dynamically loaded components. Being mainly governed by the thermal dissipation and thermal gradient in the near surface, several research groups tried to limit the phenomenon by cooling the machined surface using a cryogenic fluid. Caruso et al. (2014) applied liquid nitrogen when cutting a AISI 52,100 bearing steel. They showed that it significantly affects the in-depth residual stresses profiles but tended to induce more tensile stresses compared to cutting in dry conditions. On the contrary, Chaabani et al. (2020) recently proved that it was possible to reduce the tensile stress state by using carbon dioxide when cutting Inconel 718. When conventional machining processes, even with any type of assistance, are limited, it becomes necessary to use alternative finishing techniques. Belt finishing can be successfully employed to improve the surface roughness but also the residual stresses if the local pressure and lubrication is perfectly ensured (Rech et al. 2008). Burnishing is another relevant alternative to induce deep and intense compressive stresses, especially with the more advanced double duplex burnishing presented by Patyk et al. (2018).

Processes such as machining or burnishing not only affects the residual stresses state but also the subsurface microstructure due to the severe plastic deformations. The first observable parameter is the near surface hardness. Thamizhmanii and Hasan (2012) showed that multiple pass burnishing could progressively increase the surface hardness whereas Bordin et al. (2014) measured a 33% increase when cutting additively manufactured titanium alloy. They also noted a 20 µm layer with a highly deformed material. Indeed, several authors observed the generation of a highly deformed layer with elongated grains when burnishing of steels (Kulakowska et al. 2018) but also when cutting CrCo alloys (Bruschi et al. 2013) or even additively manufactured titanium alloys (Imbrogno et al. 2016b). Deeper investigations started to be conducted on these layers especially in hard machining where the so-called dark and white layers were reported (Habak et al. 2007; Ambrogio et al. 2012; Umbrello et al. 2011a) showed using a XRD phase analysis that white layers withstood a martensitic transformation activated by the rapid heating and quenching on the machined surface. Applying a cryogenic fluid is able to modify the thermal loadings and thus to limit the white layer thickness and reduce the associated hardness (Umbrello et al. 2011b). On the other side, an increase in the tool flank wear induces thicker white layers according to Cappellini et al. (2010).

Whereas these layers are called “white” or “dark” layers due to the color they exhibit optically once etched, many studies endeavored to precisely characterize them. Schulze et al. (2013) performed SEM analyses and showed that these layers consisted in severely refined grains when cutting AISI 4140 steel. Umbrello (2013, 2014) connected the grain size and the affected depth to the cutting parameters and especially emphasized the dependency to the cutting speed. The depth and grain size can, however, be potentially controlled depending on the selected cooling lubrication strategy, i.e. dry, cryogenic or MQL (Klocke et al. 2018a, b). In milling Inconel 718, Rinaldi et al. (2019) specified that the near surface can be divided into a highly refined layer formed above a deformed one. Dynamic recrystallization was supposed to occur below the worked surface involving a thick layer and affecting the material hardness. They also observed an increase in the thickness of the affected layer and micro-hardness when increasing the cutting speed. Whereas these mechanisms can be hard to investigate in machining, Imbrogno et al. (2017) tried to correlate the microstructure generated on the machined surface to the one obtained in the Equal Channel Angular Pressing process (ECAP). Even if, based on hardness and grain size, the microstructure after machining is deformed significantly more than in ECAP process, this first experimental approach highlighted the existence of similar physics phenomena and laid the foundation for further research.

The previously cited studies focused on the experimental investigations of the surface integrity features in different configurations. However, the state of the art issue nowadays for industry is to be able to predict such component properties. Innovative approaches such as metamodeling and genetic algorithms were already proposed eleven years ago to predict surface roughness in machining (Del Prete et al. 2010b). Simulations of residual stress generation also significantly progressed with several studies proving the prediction capability. Caruso et al. (2010) or Rizzuti and Umbrello (2011) reported a good correlation between the predicted surface residual stresses computed using a FE model and the experimentally measured ones when machining AISI H13 tool steel or titanium alloy respectively. Rizzuti et al. (2010a, b) demonstrated that the reliability of a numerical model is strictly related to its ability to properly predict both mechanical and thermal loadings applied onto the machined surface. 3D models were also developed to

achieve better prediction in milling confirming the potential of such approaches (Desmaison et al. 2011). The growing developments in numerical simulation also invited research groups to model microstructural evolution. Manco et al. (2010) successfully modelled the generation of white and dark layers whereas Imbrogno et al. (2016a) even predicted the top surface grain size and associated hardness. Their work was recently extended to predict lamellae thickness reduction and nano-hardness modifications when cutting an additively manufactured titanium alloy (Imbrogno et al. 2018b).

As a summary, the Fig. 11 shows the materials that were investigated. Besides steel, efforts were put on hard to machine materials commonly used in applications where surface integrity plays a major role such as in the nuclear, aircraft or energy industry.

Summary and future direction

Among all the published papers in the last fifteen years of the ESAFORM conference, turning seems to be one of the most studied operation as far as the macroscopic level in concerned; micro milling is the other machining operation investigated in the ESAFORM community. Regarding the materials, steels are by far the most studied, followed by Ti alloys, Ni-based alloys and composites.

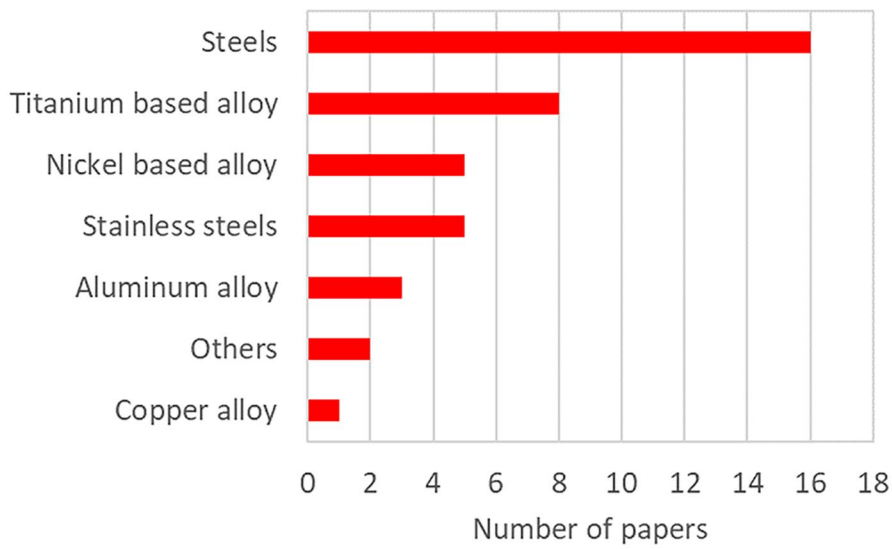

Fig. 11 Materials discussed on surface integrity in ESAFORM since 2007

Table 3 Interested variables and outputs of the material removal processes investigated in the last fifteen years within ESAFORM conferences

	Material modelling	Chip Formation	Thermal Aspects	Tool Wear	Surface Quality	Surface Integrity
2007	3	2	1	1	3	2
2008	2	2	1	5	7	5
2009	1	-	-	2	2	2
2010	8	3	1	7	9	5
2011	-	1	-	3	5	4
2012	2	1	1	3	5	2
2013	1	-	3	4	5	3
2014	4	-	2	4	4	3
2015	1	1	-	4	4	1
2016	1	2	-	2	4	3
2017	-	1	1	1	5	2
2018	1	3	-	5	7	4
2019	2	3	2	7	2	1
2020	1	2	1	1	3	1
2021	3	1	2	5	4	2
TOT.	30	22	15	54	69	40

Table 3 gives a synthesis overview as far as the mesoscopic level is concerned. In particular, contributions for each of the most interested outputs to be considered for correctly studying the material removal processes and presented in the Minisymposium on Machining and Cutting in different years are reported. Table 3 also demonstrates the relevant growth of interest associated to the experimental and numerical studies of the material removal processes.

In particular, the evolution of studies on chip formation in recent years shows that this theme develops around two distinct axes: (i) traditional and conventional study of chip formation at the macro-meso scale for new materials, or for new machining configurations, such as cutting assistance. These studies make it possible to optimize the process parameters to improve the industrial process; (ii) study of chip formation zones by rapid imaging observation and numerical simulations. The local observation of deformation zones by high-speed cameras makes it possible to see machining no longer as a process, but as a means of deforming the material in extreme conditions. The scientific problem is to calculate the strain and strain rate in these areas (generally done by digital image correlation), but also to measure geometric values (shear angle, shape of the elementary chip, etc.) automatically by image analysis using machine learning or deep learning algorithms. This approach by observation is limited to the surface of the workpiece although it permits to carry out numerical simulations more reliable in order to know the mechanical and thermal fields over the entire cutting volume.

Also, the analysis of thermal fields in machining has always been difficult due to the very high temperatures and the very strong gradient of the chip formation zone. The evolution of past work shows that future studies are developing around a coupled approach between non-contact observation by thermal cameras and numerical simulations. The scientific problem is to have reliable local thermal measurements, which is not easy because the observation area is very restricted and the involved phenomena very fast.

Control of tool wear is also a critical issue in terms of the product quality and production efficiency. The tool wear has been discussed with abrasive, adhesion and diffusion models so far. However, the actual tool wear mechanism depends on many physical/chemical phenomena. New models will include the other effects on the wear progress to promote prediction accuracy and describe the tool wear in the scientific discussion. High computational power will be also required for simulation of the tool wear. It is well known that the tool wear is associated with the temperature distribution on the tool face. The accurate temperature analysis should be done with consideration of the coolant effects, the fixturing conditions, and so on. The performance of the tool wear prediction will be improved with the temperature analysis.

As far as the material modeling is concerned, with the growing computational power, approaches based on crystal plasticity could be used to a larger extent and especially concerning data at the micro scale. This could be relevant to face challenges when modelling finishing technologies, small uncut chip thickness processes or micro machining. Such numerical models can be used as an advanced way to generate virtual data to be used for covering a wide ranges of inputs parameters, geometries, conditions, etc. Future trends are oriented on developing digital twins-based models which could be connected in real time to the actual machining operation.

Finally, better information about three dimensional processes have to be provided where new manufacturing processes or even for conventional processes not well studied, need to be investigated. Some examples could be machining (reaming) of flexible components with slender tools, gear hobbing, machining of near net shape components, etc. Providing in agile way customized solutions will be a must to reduce costs and as well lower environmental impact.

As overall, experimental and numerical study of material removal processes still represents a key issue for the future. In the case of experimental data, information gathered not only at laboratory level but as well in production plants could help developing robust models data driven. Development of such technologies in the future, also considering the additive and subtractive hybrid processes could represent a remarkable breakthrough. Especially for this new hybrid process, but also for the micro and nano technologies, scientific research in this field is still complex. Aspects such machinability for multimaterials o functionally graded materials will need to be considered, and optimized working conditions will need to be provided. Additionally, aspects dealing will microstructure will need to be considered, trying to better define the current uncertainty observed in some industrial outcomes for the conventional materials in aspects such as chip morphology, surface roughness, etc.

Acknowledgements Authors wish to thank all the researchers that in these fifteen years have published and presented their researches within the Minisymposium on Machining and Cutting during the ESAFORM Conferences. Only thanking them we were able to write this extensive review.

Declarations

Conflict of interest The authors declare that they have not conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this

article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Agirreurreta AA, Pelegay JA, Arrazola PJ, Orskov KB, Chinesta F, Cueto E, Abisset-Chavanne E (2016) High productivity machining of holes in Inconel 718 with SiAlON tools, AIP Conference Proceedings 1769, 080006

Amaro P, Ferreira P, Simões F (2018) Tool wear analysis during duplex stainless steel trochoidal milling. AIP Conference Proceedings, 1960, 070001

Amaro P, Ferreira P, Simões F (2020) Comparative analysis of different cutting milling strategies applied in duplex stainless steel. Procedia Manuf 47:517–524

Ambrogio G, Di Renzo S, Gagliardi F, Umbrello D (2012) White and Dark Layer Analysis Using Response Surface Methodology.Key Engineering Materials,504–506, pp. 1335–1340

Angiuli R, Giannuzzi M, Papadia G (2019) Experimental thermographic investigation for dry finish turning of SAF 2507 steel. AIP Conference Proceedings, 2113, art. no. 080004, DOI: https://doi.org/10.1063/1.5112612

Andreas K, Engel U, Merklein M (2012) Influence of Grinding on the Surface Properties of Cemented Carbides.In Key Engineering Materials,504–506, pp. 1353–1358

Arrazola PJ, Barbero O, Urresti I (2010) Influence of material parameters on serrated chip prediction in finite element modeling of chip formation process. International Journal of Material Forming, 3 (SUPPL. 1), pp. 519–522

Arrazola PJ, Özel T, Umbrello D, Davies M, Jawahir IS (2013a) Recent advances in modelling of metal machining processes. CIRP Annals - Manufacturing Technology 62(2):695–718

Arrazola PJ, Matsumura T, Armentia I, Kortabarria A (2013b) Thermo mechanical loads In Ti-6Al-4V machining.Key Engineering Materials,554–557, pp. 2047–2053

Arrieta I, Courbon C, Cabanettes F, Arrazola PJ, Rech J (2017) Influence of the ferritic-pearlitic steel microstructure on surface roughness in broaching of automotive steels, AIP Conference Proceedings 1896, 090011

Asad M, Girardin F, Mabrouki T, Rigal J-F (2008) Dry cutting study of an aluminium alloy (A2024-T351): A numerical and experimental approach. IntJ Mater Form 1:499–502

Attanasio A, Ceretti E, Giardini C, Filice L, Umbrello D (2008) Criterion to evaluate diffusive wear in 3D simulations when turning AISI 1045 steel. Int J Mater Form 1:495–498

Attanasio A, Umbrello D (2009) Abrasive and diffusive tool wear FEM simulation. Int J Mater Form 2:543–546

Attanasio A, Ceretti E, Giardini C (2011) 3D FEM simulation of flank wear in turning, AIP Conference Proceedings, 1353, 561

Ayed Y, Germain G, Ammar A, Furet B (2013) Experimental study of tool wear mechanisms in conventional and high pressure coolant assisted machining of titanium alloy Ti17.Key Engineering Materials,554–557, 1961–1966

Batista M, Calamaz M, Girot F, Salguero J, Marcos M (2012) Using image analysis techniques for single evaluation of the chip shrinkage factor in orthogonal cutting process.Key Engineering Materials,504–506, pp. 1329–1334

Bellin M, Sartori S, Ghiotti A, aBruschi S (2017) New tool holder design for cryogenic machining of Ti6Al4V, AIP Conference Proceedings 1896, 090001

Benhassine M, Rivière-Lorphèvre E, Arrazola P-J, Gobin P, Dumas D, Madhavan V, Aizpuru O, Ducobu F (2018) 2D simulations of orthogonal cutting of CFRP: Effect of tool angles on parameters of cut and chip morphology. AIP Conference Proceedings, 1960, art. no. 070005

Benhassine M, Rivière-Lorphèvre E, Arrazola P-J, Gobin P, Granjon A, Aizpuru O, Ducobu F (2019) Finite-element simulations of Al7075-T6 orthogonal cutting: Effect of part geometry and mesh on chip morphology and formation mechanism. AIP Conference Proceedings, 2113, art. no. 080003

Ben Boubaker H, Ayed Y, Mareau C, Germain G (2018) "On the formation of adiabatic shear bands in titanium alloy Ti17 under severe loading conditions", AIP Conference Proceedings 1960, 070004

Bertolini R, Ghiotti A, Bruschi S (2021) Cryogenic machining to enhance surface finish of a biomedical grade ultra-high-molecular weight polyethylene. 24th International Conference on Material Forming, Liège, Belgique

Biermann D, Höhne F, Sieben B et al (2010) Finite element modeling and three-dimensional simulation of the turning process incorporating the material hardness. Int J Mater Form 3, 459–462 (2010)

Bonnet C, Pottier T, Landon Y, Bouzid A (2021) Validation of a multiscale Ti-6Al-4V drilling model by means of thermomechanical field measurements, Liegi, Belgium

Bordin A, Bruschi S, Ghiotti1 A, Bucciotti F, Facchini L (2014) Comparison between wrought and EBM Ti6Al4V machinability characteristics.Key Engineering Materials,611–612, 1186–1193

Braham-Bouchnak T, Germain G, Robert P, Lebrun JL (2010) High pressure water jet assisted machining of duplex steel: machinability and tool life. Int J Mater Form 3:507–510

Boubakri C, Wolff NM, Moufki A, Dubar L, Watremez M, Hubert C (2019) Micromachining simulation using a crystal plasticity model: ALE and CEL approaches, AIP Conference Proceedings 2113, 080017

Bordin A, Imbrogno S, Bruschi S, Ghiotti A, Umbrello D (2015) Numerical Modelling of Orthogonal Cutting of Electron Beam Melted Ti6Al4V.Key Engineering Materials,651–653, 1255–1260

Bruschi S, Ghiotti A, Bordin A (2013) Effect of the Process Parameters on the Machinability Characteristics of a CoCrMo Alloy.In Key Engineering Materials,554–557, pp. 1976–1983

Burns TJ, Mates S, Rhorer RL et al (2010) Modeling of the temperature field in the chip and in the tool in high-speed machining of a carbon steel: effect of pearlite to austenite phase

Cappellini C, Attanasio A, Rotella G, Umbrello D (2010) Formation of white and dark layers in hard cutting: influence of tool wear. IntJ Mater Form 3:455–458

Careri F, Imbrogno S, Attallah MM, Essa K, Umbrello D (2020) Finite element modeling of machining nickel superalloy produced by direct energy deposition process. Procedia Manuf 47:525–529

Caruso S, Outeiro JC, Umbrello D, M'Saoubi R (2010) Modeling and experimental validation of the surface residual stresses induced by hard machining of AISI H13 tool steel. IntJ Mater Form 3:515–518

Caruso S, Outeiro JC, Umbrello D, Batista AC (2014) Residual Stresses in Machining of AISI 52100 Steel under Dry and Cryogenic Conditions: A Brief Summary.Key Engineering Materials,611–612, pp. 1236–1242

Caruso S, Rinaldi S, Franchi R, Del Prete A, Umbrello D (2017) Experimental analysis of influence of cutting conditions on machinability of waspaloy. AIP Conference Proceedings, 1896, art. no. 090008

Chaabani S, Rodriguez I, Cuesta M, Ayed Y, Arrazola PJ, Germain G (2019) Tool wear and cutting forces when machining inconel 718

under cryogenic conditions: Liquid nitrogen and carbon dioxide. AIP Conference Proceedings, 2113, art. no. 080002
Chaabani S, Arrazola PJ, Ayed Y, Madariaga A, Tidu A, Germain G (2020) Surface integrity when machining Inconel 718 using conventional lubrication and carbon dioxide coolant. Procedia Manuf 47:530–534
Chinesta F, Filice L, Micari F et al (2008) Assessment of material models through simple machining tests. Int J Mater Form 1:507–510
Chodor J, Kukielka L, Kaldunski P, Bohdal L, Patyk R, Kulakowska A (2018) Evaluation of the correctness of the feed selection based on the analysis of chip's shape. AIP Conference Proceedings, 1960, art. no. 070007
Courbon C, Mabrouki T, Rech J et al (2010) On the identification conditions of a constitutive model in machining of AISI 1045 steel. Int J Mater Form 3:439–442
Courbon C, Mabrouki T, Rech J, Mazuyer D, Perrard F, D'Eramo E (2013) Metallurgical Aspects of Material Behaviour in Cutting of AISI 1045.Key Engineering Materials,554–557, pp. 2085–2092
David T, Methon G, M'Saoubi R, Girinon M, Rech J, Courbon C (2021) Characterization of wear modes in orthogonal milling of 15-5PH stainless steel. ESAFORM 2021
Del Prete A, Vitis AA, Spagnolo A (2010a) Experimental development of RSM techniques for surface quality prediction in metal cutting applications. IntJ Mater Form 3:471–474
Del Prete A, De Vitis AA, Anglani A (2010b) Roughness improvement in machining operations through coupled metamodel and genetic algorithms technique. IntJ Mater Form 3:467–470
Del Prete A, De Vitis AA, Filice L, Caruso S, Umbrello D (2012) Tool engage investigation in nickel superalloy turning operations.Key Engineering Materials,504–506, 1305–1310
Desmaison O, Mocellin K, Jardin N (2011) Modelling of Residual Stresses Induced By High Speed Milling Process, AIP Conference Proceedings 1353, 597–602
Denkena B, Ammermann C, Niederwestberg D (2012) Development of a calorimeter to determine the chip heat in drilling of C45EN. Key Eng Mater 504–506. DOI: https://doi.org/10.4028/www.scientific.net/KEM.504-506.1341
Dornfeld D, Min S, Takeuchi Y (2006) Recent Advances in Mechanical Micromachining. Cirp Annals – Manufacturing Technology 55(2):745–768
Drobnič M, Pušavec F, Čekada M (2021) Liquid LCO2 Assisted Machining of Martensitic Stainless Steel with TiAlSiN PVD Coated Tools. 24th International Conference on Material Forming, Liège, Belgique
Ducobu F, Arrazola P-J, Rivière-Lorphèvre E, Filippi E (2015) Comparison of several behaviour laws intended to produce a realistic Ti6Al4V chip by finite elements modelling.Key Engineering Materials,651–653, pp. 1197–1203
Ducobu F, Demarbaix A, Pantalé O (2021) Finite element modelling of the Taylor impact test in 3D with the Coupled Eulerian-Lagrangian method. 24th International Conference on Material Forming, Liège, Belgique
Equeter L, Ducobu F, Rivière-Lorphèvre E, Abouridouane M, Klocke F, Dehombreux P (2018) Estimation of the influence of tool wear on force signals: a finite element approach in AISI 1045 orthogonal cutting. AIP Conference Proceedings 1960, 070012
Fabre D, Bonnet C, Rech J, Mabrouki T (2016) Iterative Lagrangian model of broaching to study cutting forces, temperatures and chip formation. AIP Conference Proceedings, 1769, art. no. 080003
Fergani O, Jiang X, Welo T (2016) Analysis of residual stress-induced distortions of thin sheet structures in multi-step milling, AIP Conference Proceedings 1769, 080014
Ferreira P, Simões F, Relvas C (2014) Experimental analysis of milling operations in Ti-6Al-4V and Co-28Cr-6Mo alloys for medical devices.Key Engineering Materials,611–612, pp. 1282–1293
Filice L, Micari F, Rizzuti S, Umbrello D (2007) A critical analysis on the friction modeling in orthogonal cutting of steel. AIP Conference Proceedings, 907, pp. 745–750
Franco P, Estrems M, Faura F (2007) Numerical modelling of tool wear in turning with cemented carbide cutting tools. AIP Conference Proceedings 907, 715
Fukumori S, Itoigawa F, Maegawa S, Nakamura T, Shamoto E (2019) Suppression mechanism of diamond tool wear in ultrasonic vibration cutting. AIP Conference Proceedings. 2113. 080020
Ganesan SM, Khan YA, Valberg H et al (2008) Cutting applied as test method for acquisition of flow stress data at high strains and strain rates. Int J Mater Form 1:519–522
Germain G, Lebrun JL, Braham-Bouchnak T, Bellett D, Auger S (2008) Laser-assisted machining of Inconel 718 with carbide and ceramic DOI: 10.1007/s12289-008-0213-y. All Open Access, Green, OPEN ACCESS
Giovenco A, Courbon C, Cabanettes F, Rech J, Masciantonio U, Karaouni H, D'Eramo E, Van Robaeys A, Jourden E (2019) Importance of the contact interface definition in the numerical simulation of tool wear in metal cutting. AIP Conference Proceedings, 2113, 080007
Girardin F, Remond D, Rigal J-F (2010) A new method for detecting tool wear and breakage in milling. Int J Mater Form 3:463–466
Gravier J, Vignal V, Bissey-Breton S, Farré J (2008) Impact of cutting conditions on mechanical, microstructural and electrochemical state in super finish turning of copper. IntJ Mater Form 1:527–530
Gutowski T, Murphy C, Allen D, Bauer D, Bras B, Piwonka T, Sheng P, Sutherland J, Thurston D, Wolff E (2005) Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States. J Clean Prod 13(1):1–17
Habak M, Lebrun JL, Morel A (2007) A study of the influence of the metallurgical state on shear band and white layer generation in 100Cr6 steel: application to machining, AIP Conference Proceedings 907, 691–696
Haddag B, Nouari M, Moufki A (2016) Some cases of machining large-scale parts: Characterization and modelling of heavy turning, deep drilling and broaching. AIP Conference Proceedings, 1769, art. no. 080004
Harzallah M, Pottier T, Senatore J, Mousseigne M, Germain G, Landon Y (2016) A new behavior model for better understanding of titanium alloys Ti-6Al-4V chip formation in orthogonal cutting, AIP Conference Proceedings 1769, 080015
He Y, Li L-N, Li C-Y, Chen L, Yue X (2013) Experimental investigation on the cutting heat distribution with different coating structures inserts.Key Engineering Materials,554–557, pp. 1953–1960
Imbrogno S, Rotella G, Umbrello D (2014) On the Flow Stress Model Selection for Finite Element Simulations of Machining of Ti6Al4V. Key Engineering Materials, Vols. 611–612, pp. 1274–1281
Imbrogno S, Rinaldi S, Seara B, Arrazola PJ, Rotella G, Umbrello D (2016a) 2D finite element model and microstructural changes during cutting of Ti6Al4V in dry condition, AIP Conference Proceedings 1769, 080010
Imbrogno S, Bordin A, Bruschi S, Umbrello D (2016b) Experimental analysis on semi-finishing machining of Ti6Al4V additively manufactured by direct melting laser sintering, AIP Conference Proceedings 1769, 080007 https://doi.org/10.1063/1.4963482
Imbrogno S, Segebade E, Fellmeth A, Gerstenmeyer M, Zanger F, Schulze V, Umbrello D (2017) Microstructural and hardness changes in aluminum alloy Al-7075: Correlating machining and equal channel angular pressing, AIP Conference Proceedings 1896, 090005
Imbrogno S, Rinaldi S, Suarez AG, Arrazola PJ, Umbrello D (2018a) High speed machinability of the aerospace alloy AA7075 T6 under different cooling conditions. AIP Conference Proceedings, 1960, art. no. 070013

Imbrogno S, Rinaldi S, Raso A, Bordin A, Bruschi S, Umbrello D (2018b) 3D FE simulation of semi-finishing machining of Ti6Al4V additively manufactured by direct metal laser sintering, AIP Conference Proceedings 1960, 070014

Jafarian F, Ciaran MI, Arrazola PJ, Filice L, Umbrello D, Amirabadi H (2014) Effects of the Flow Stress in Finite Element Simulation of Machining Inconel 718 Alloy. In Key Engineering Materials (Vols. 611–612, pp. 1210–1216

Jayal AD, Badurdeen F, Jawahir D Jr, I.S (2010) Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP J Manufact Sci Technol 2(3):144–152

Jawahir IS, Balaji AK (2000) Predictive Modeling and Optimization of Turning Operations with Complex Grooved Cutting Tools for Curled Chip Formation and Chip Breaking. Mach Sci Technol 4(3):399–443

Jegatheesan V, Liow JL, Shu L, Kim SH, Visvanathan C (2009) The Need for Global Coordination in Sustainable Development. J Clean Prod 17(7):637–643

Jovane F, Yoshikawa H, Alting L, Boër CR, Westkamper E, Williams D, Tseng M, Seliger G, Paci AM (2008) The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing. CIRP Ann Manuf Technol 57(2):641–659

Kalhori V, Wedberg D, Lindgren L (2010) Simulation of mechanical cutting using a physical based material model. IntJ Mater Form 3:511–514

Klocke F, Lung D, Krämer A, Cayli T, Sangermann H (2013) Potential of modern lubricoolant strategies on cutting performance.Key Engineering Materials,554–557, pp. 2062–2071

Klocke F, Döbbeler B, Lung S, Seelbach T, Jawahir IS (2018a) Analysis of surface integrity in machining of AISI 304 stainless steel under various cooling and cutting conditions, AIP Conference Proceedings 1960, 070015

Klocke F, Döbbeler B, Lakner T (2018b) Impact of high-pressure coolant supply on chip formation in milling Impact of High-Pressure Coolant Supply on Chip Formation in Milling.Procedia CIRP.77

Komatsu T, Matsumura T, Yoshino T, Torizuka S (2011) Micro cutting process of ultra fine grain steels. AIP Conference Proceedings, 1353, pp. 585–590

Kugalur-Palanisamy N, Riviere-Lorphèvre E, Arrazola P-J, Ducobu F (2019) Comparison of Johnson-Cook and modified Johnson-Cook material constitutive models and their influence on finite element modelling of Ti6Al4V orthogonal cutting process. AIP Conference Proceedings, 2113, art. no. 080009

Kugalur-Palanisamy N, Rivière-Lorphèvre E, Ducobu F, Arrazola P-J (2020) Influence of the choice of the parameters on constitutive models and their effects on the results of Ti6Al4V orthogonal cutting simulation. Procedia Manuf 47:458–465

Kugalur-Palanisamy N, Rivière-Lorphèvre E, Arrazola P, Ducobu F (2021) Influences of Cutting Speed and Material Constitutive Models on Chip Formation and their Effects on the Results of Ti6Al4V Orthogonal Cutting Simulation. 24th International Conference on Material Forming, Liège

Kulakowska A, Kukielka L, Kaldunski P, Bohdal L, Patyk R, Chodor J, Kukielka K (2018) Burnishing rolling process of the surface prepared in the turning process, AIP Conference Proceedings 1960, 070016

Le Mercier K, Watremez M, Fouilland L, Guérin JD, Dubar L (2014) Thermo-Mechanical Behaviour of Spheroidal Graphite Iron. Engineering Materials, Vols.611–612, pp. 1250–1257

Lorong P, Micari F, Touratier M (2007) Modelling of Cutting and Machining: 10 years of ESAFORM activity, Advances in Material Forming. Springer, pp 225–236

Lu T, Gupta A, Jayal AD, Badurdeen F, Feng SC, Dillon OW Jr, Jawahir IS (2011) A Framework of Product and Process Metrics for Sustainable Manufacturing, Advances in Sustainable Manufacturing, pp. 331–336

Makarov VF, Tokarev D, Tyktamishev VR (2008) High speed broaching of hard machining materials. IntJ Mater Form 1:547–550

Manco GL, Caruso S, Rotella G (2010) FE modeling of microstructural changes in hard turning of AISI 52100 steel. IntJ Mater Form 3:447–450

Mäntyjärvi K, Väisänen A, Karjalainen JA (2009) Cutting method influence on the fatigue resistance of ultra-high-strength steel. IntJ Mater Form 2:547–550

Makhfi S, Malek Habak M, Velasco R, Haddouche K, Vantomme P (2011) Prediction of Cutting Forces Using ANNs Approach in Hard Turning of AISI 52100 steel, AIP Conference Proceedings, 1353, 669–674

Marouvo J, Ferreira P, Simões F (2021) Cutting Performance of Austenitic and Duplex Stainless Steels with Drills of Three Cutting Edges. Paper presented at ESAFORM 2021. 24th International Conference on Material Forming, Liège, Belgique. doi: https://doi.org/10.25518/esaform21.4284

Matsumura T, Shirakashi T, Usui E (2008) Identification of wear characteristics in tool wear model of cutting process. International Journal of Material Forming, 1 (SUPPL. 1), pp. 555–558

Matsumura T, Hori I, Shirakashi T (2010) Analysis of cutting temperature in drilling process. International Journal of Material Forming, 3 (SUPPL. 1), pp. 499–502

Maurel A, Michel G, Thibaud S, Fontaine M, Gelin JC (2007) Inverse Method for Identification of Material Parameters Directly from Milling Experiments, AIP Conference Proceedings 907, 739–744

Mehrban M, Naderi D, Panahizadeh V, Naeini HM (2008) Modelling of tool life in turning process using expermental method. Int J Mater Form 1:559–562

Meena A, El Mansori M (2016) Cutting performance and wear mechanisms of PVD coated carbide tools during dry drilling of newly produced ADI. 1769:080011. https://doi.org/10.1063/1.4963486

Melkote SN, Grzesik W, Outeiro J, Rech J, Schulze V, Attia H, Arrazola PJ, M'Saoubi R, Saldana C (2017) Recent Advances in Mechanical Micromachining. Cirp Annals – Manufacturing Technology 66(2):731–754

Merchant M (1998) An interpretive look at twentieth century research on modeling of machining. Mach Sci Technol 2(2):157–163

Montoya M, Calamaz M, Gehin D, Girot F (2014) Numerical simulation of workpiece thermal field in drilling CFRP/aluminum alloy. Key Engineering Materials, 611–612, pp. 1226–1235. DOI: https://doi.org/10.4028/www.scientific.net/KEM.611-612.1226 OPEN ACCESS: All Open Access, Green

Obikawa T, Funai K (2013) Air Jet Assisted Machining of Inconel 718 with Whisker Reinforced Ceramic Tool. KEM. https://doi.org/10.4028/www.scientific.net/kem.554-557.2079

Obikawa T, Nakatsukasa R, Hayashi M, Ohno T (2018) High performance cutting using micro-textured tools and low pressure jet coolant. AIP Conference Proceedings, 1960, 070019

Obikawa T, Matsumoto W, Hayashi M (2019) Influence of coolant flow on tool wear under jet cooling conditions. AIP Conference Proceedings, 2113, 080012

Patyk R, Kukielka L, Kaldunski P, Bohdal L, Chodor J, Kulakowska A, Kukielka K, Nagnajewicz S (2018) Experimental and numerical researches of duplex burnishing process in aspect of achieved productive quality of the product, AIP Conference Proceedings 1960, 070021 https://doi.org/10.1063/1.5034917

Pittalà GM, Monno M (2010) Flow stress determination in orthogonal cutting process combining the primary and the secondary shear zones. IntJ Mater Form 3:483–486

Rabinowicz E, Dunn LA, Russel PG (1961) A Study of abrasive wear under three-body condition. Wear 4(5):345–355

Rech J, Kermouche G, Claudin C, Khellouki A, Grzesik W (2008) Modelling of the residual stresses induced by belt finishing on a AISI52100 hardened steel. IntJ Mater Form 1:567–570

Rinaldi S, Umbrello D, Rizzuti S, Mocchi B (2019) Experimental analysis of high speed milling using a ceramic tool, AIP Conference Proceedings 2113, 080011

Rinaldi S, Umbrello D, Rotella G, Del Prete A (2020) A physically based model to predict microstructural modifications in Inconel 718 high speed machining. Procedia Manuf 47:487–492

Rizzuti S, Umbrello D, Filice L, Settineri L (2010a) Finite element analysis of residual stresses in machining. IntJ Mater Form 3:431–434. 10.1007/s12289-010-0799-8

Rinaldi S, Umbrello D (2021) Waspaloy orthogonal hard machining simulation, a comparison among different rheological models. Paper presented at ESAFORM 2021. 24th International Conference on Material Forming, Liège, Belgique

Rizzuti S, Umbrello D, Filice L, Settineri L (2010b) Finite element analysis of residual stresses in machining. IntJ Mater Form 3:431–434

Rizzuti S, Umbrello D (2011) Finite Element Simulation of Machining of Ti6Al4V Alloy, AIP Conference Proceedings 1353, 633–638

Saanouni K, Belamri N, Autesserre P (2009) 3D numerical simulation of anisotropic thin sheet metal slitting process using fully coupled constitutive equations including ductile damage. IntJ Mater Form 2:535–538

Sáez-de-Buruaga M, Poveda I, Arrazola PJ (2015) Tool Wear Prediction in Machining Process Using a Microstructure-Based Finite Element Model,Key Engineering Materials Vols.651–653, pp. 1229–1234

Saffioti MR, Sanguedolce M, Rotella G, Filice L (2021a) On the Effects of Burnishing Process on Tribological Surface Resistance of Additively Manufactured Steel. 24th International Conference on Material Forming, Liège, Belgique

Saffioti M, Sanguedolce M, Rotella G, Umbrello D (2021b) Experimental analysis on machining parameters and cooling conditions affecting surface integrity of Ti6Al4V. 24th International Conference on Material Forming, Liège, Belgique

Sartori S, Bordin A, Bruschi S, Ghiotti A (2015) Machinability of the EBM Ti6Al4V in Cryogenic Turning. Key Engineering Materials, Vols. 651–653, pp. 1183–1188

Schulze V, Zanger F, Ambrosy F (2013) Investigation of the Impact of Orthogonal Cutting Processes on Nanocrystalline Surface Layer Generation.Key Engineering Materials,554–557, 2009–2020

Segurajauregui U, Masset L, Arrazola PJ (2007) Improving Quality in Machined Automotive Parts with the Finite Element Method, AIP Conference Proceedings 907, 769–774

Sela A, Ortiz-de-Zarate G, Soriano D, Cuesta M, Arrieta I, Arrazola PJ (2019) Towards inverse simulation: Effect of material parameters on machining predictions, AIP Conference Proceedings 2113, 080021

Shrot A, Bäker M (2010) Is it possible to identify Johnson-Cook law parameters from machining simulations? IntJ Mater Form 3:443–446

Shrot A, Bäker M (2012) Material Parameter Identification from Machining Simulations Using Inverse Techniques. In Key Engineering Materials, Vols. 504–506, pp. 1281–1286

Takeyama H, Murata T (1963) Basic investigations on tool wear. Transactions of the ASME. J Eng Ind 85(1):33–38

Tamura S, Matsumura T (2021) Cutting Force in Milling of Additive Manufacturing AISI 420 Stainless Steel. 24th International Conference on Material Forming, Liège, Belgique

Thamizhmanii S, Hasan S (2012) Performance of tool wear using cryogenic treated CBN inserts. Key Eng Mater 504–506:1323–1328

Teti R (2002) Machining of Composite Materials. Cirp Annals – Manufacturing Technology 51(2):611–634

Thibaud S, Touache A, Chambert J, Picart P (2007) A New Modelling of Dynamic Recrystallization — Application to Blanking Process of Thin Sheet in Copper Alloy. AIP Conference Proceedings 907, 703–708

Tiffe M, Biermann D, Zabel A (2014) Fitting of Constitutive Material Parameters for FE-Based Machining Simulations for Functionally Graded Steel Components.Key Engineering Materials, Vols.611–612, pp. 1202–1209

Tirelli S, Chiappini E, Strano M, Monno M, Semeraro Q (2014) Experimental comparison between traditional and cryogenic cooling conditions in rough turning of Ti-6Al-4V.Key Engineering Materials,611–612, 1174–1185

Tirelli S, Chiappini E, Strano M, Monno M, Semeraro Q (2015) Economical comparison of cryogenic vs. traditional turning of Ti-6Al-4V: a case study.Key Engineering Materials,651–653, 1204–1210

Umbrello D, Rizzuti S, Outeiro JC, Shivpuri R (2007) Modeling of the flow stress for AISI H13 Tool Steel during Hard Machining Processes, AIP Conference Proceedings 907, 775–780

Umbrello D, Filice L, Micari F, Matsumura T, Shirakashi T (2008) Prediction of tool wear progress in machining of carbon steel using different tool wear mechanisms. Int J Mater Form 1:571–574

Umbrello D, Rotella G, Crea F (2011a) Experimental Investigation of White Layer formation in Hard Turning, AIP Conference Proceedings 1353, 621–626

Umbrello D, Caruso S, Renzo SD, Jayal AD, Jawahir D Jr (2011b) I. S. Dry vs. cryogenic orthogonal hard machining: an experimental investigation. AIP Conference Proceedings 1353, 627

Umbrello D, Caruso S, Rotella G (2012) Hardness-Based Flow Stress for Numerical Simulation of Machining Inconel 718 Alloy.Key Engineering Materials,504–506, 1287–1292

Umbrello D (2013) The Effects of Cutting Conditions on Surface Integrity in Machining Inconel 718 Alloy.Key Engineering Materials,554–557, 2093–2100

Umbrello D (2014) The Effects of Cutting Conditions on Surface Integrity in Machining Waspaloy. Key Eng Mater 611–612:1243–1249

Usui E, Shirakashi S, Kitagawa T (1984) Anal Prediction Tool Wear Wear 100(1–3):129–151

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.