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ESAFORM 25 YEARS ON

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

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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

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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).

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.

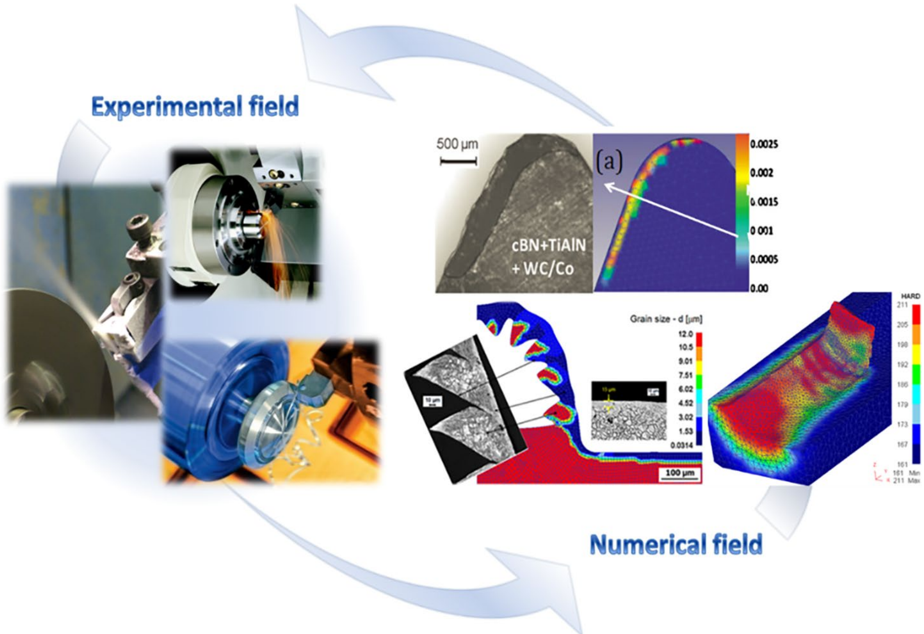

Fig. 1 Finite elements output results used by industries to predict the machining performance experimentally evaluated (Arrazola et al. 2013a)

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

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)

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.

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 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

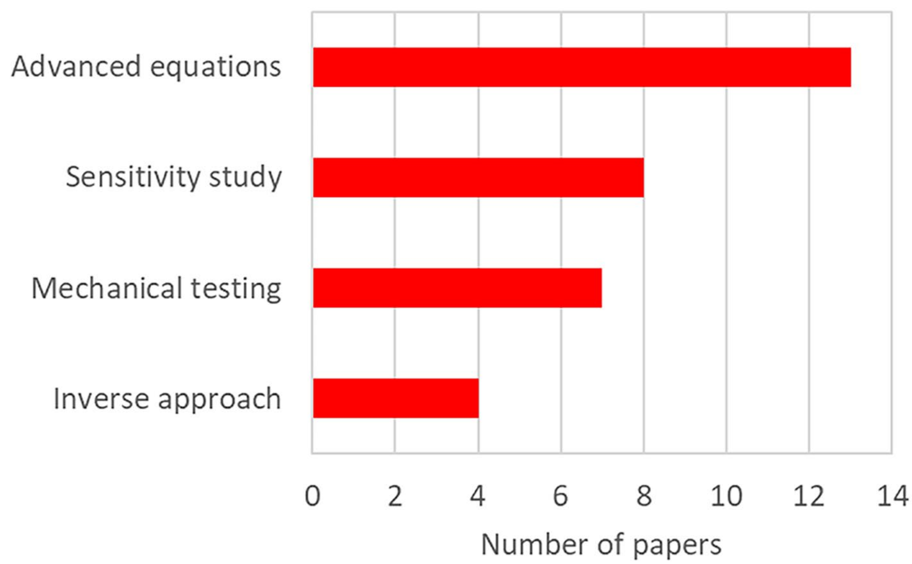

Fig. 2 Papers focusing on material modelling in ESAFORM since 2007

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).

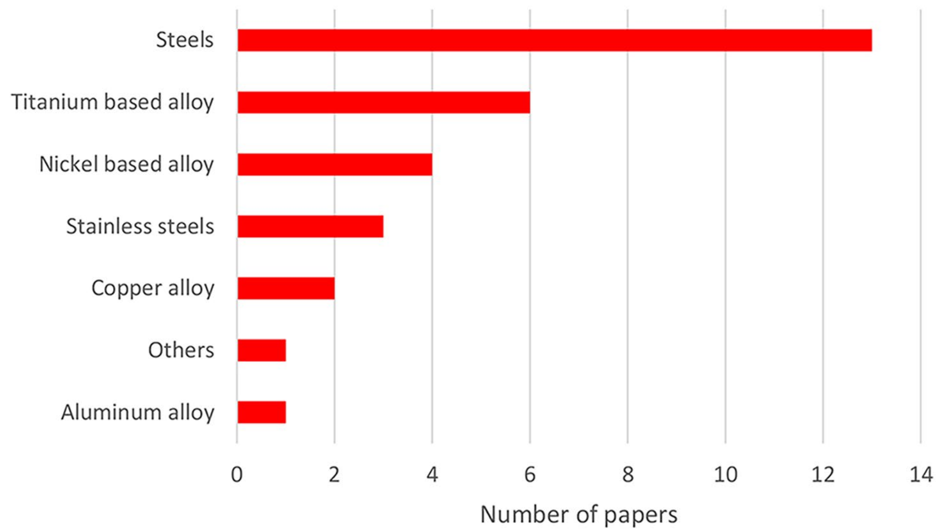

Fig. 3 Materials discussed on material modelling in ESAFORM since 2007

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.

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,

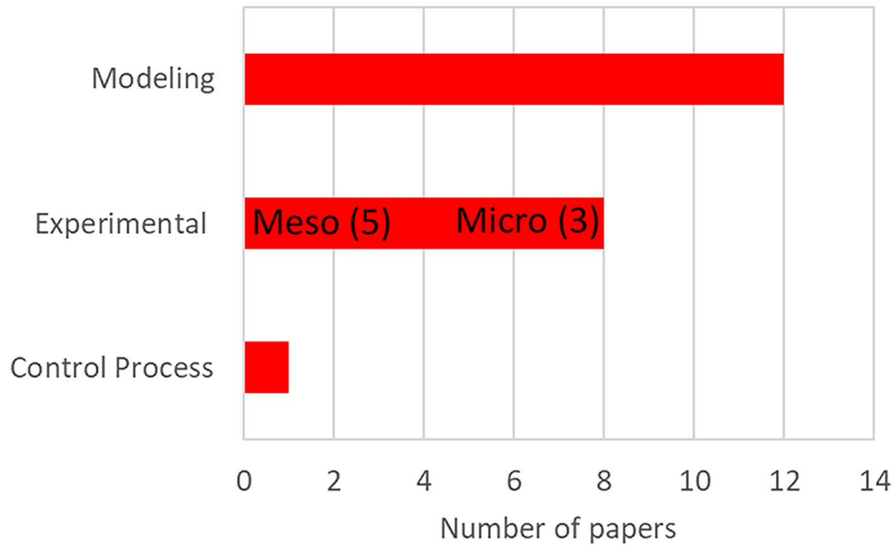

Fig. 4 Papers focusing on chip formation in ESAFORM since 2007

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

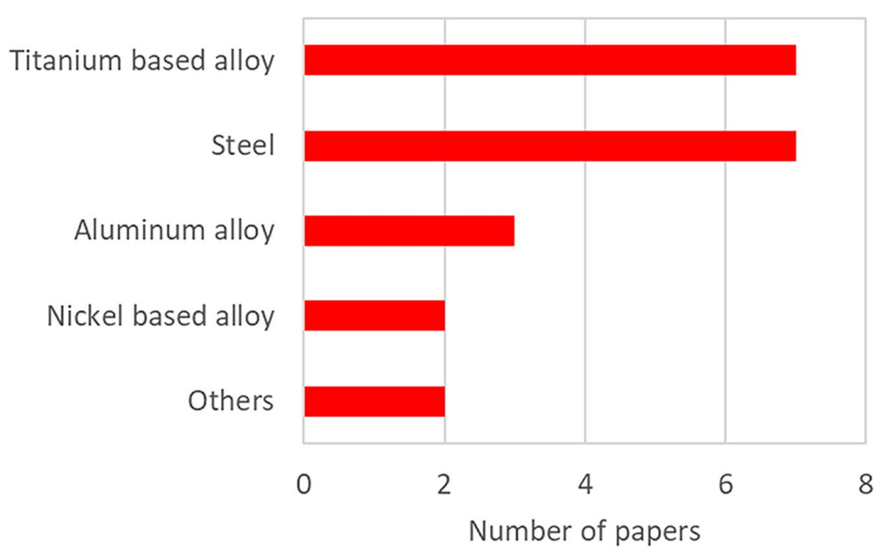

Fig. 5 Materials discussed on chip formation in ESAFORM since 2007

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 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 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; (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

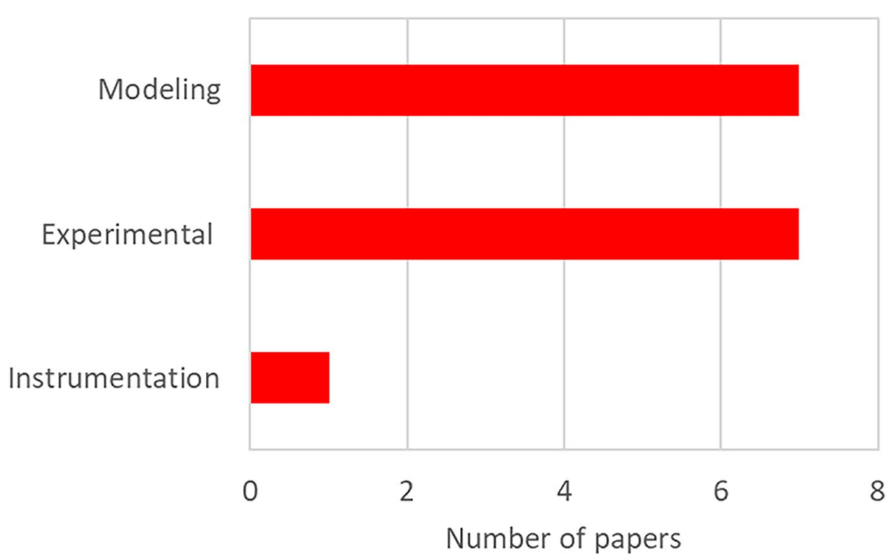

Fig. 6 Papers focusing on thermal aspects in ESAFORM since 2007

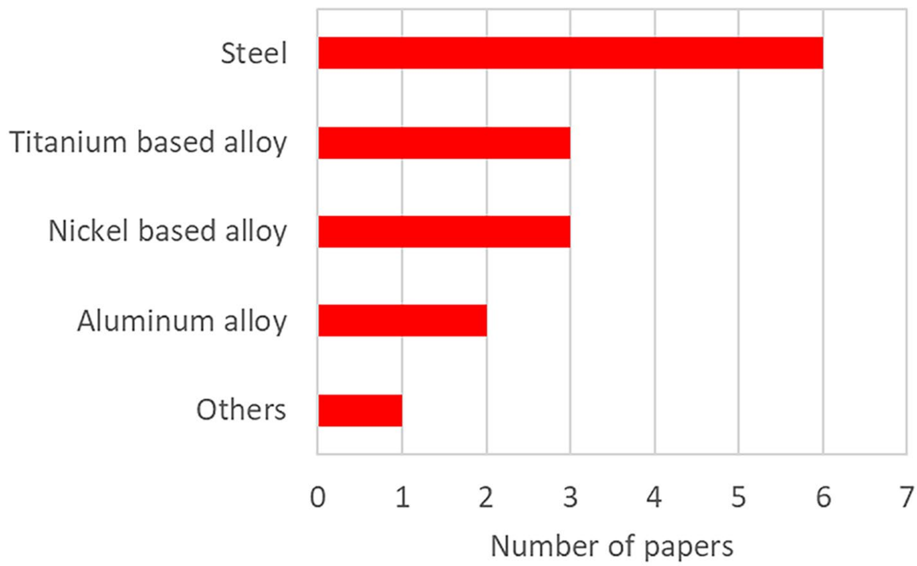

Fig. 7 Materials discussed on chip formation in ESAFORM since 2007

(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

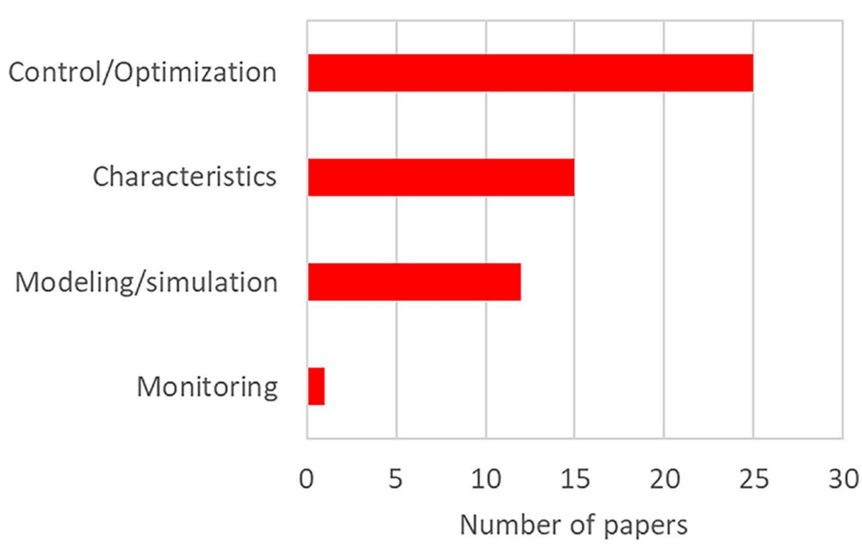

Fig. 8 Papers focusing on tool wear presented in ESAFORM since 2007

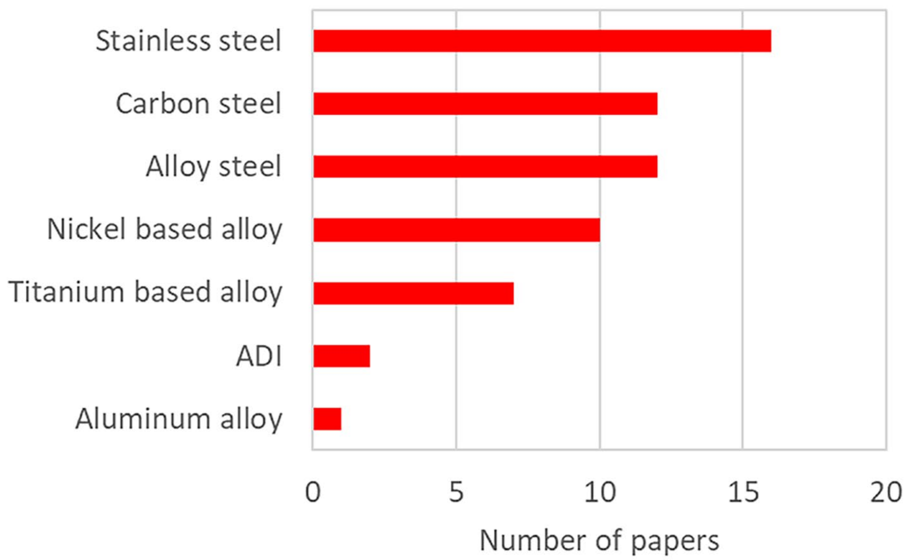

Fig. 9 Materials discussed in ESAFORM since 2007

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 sub-zero 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 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

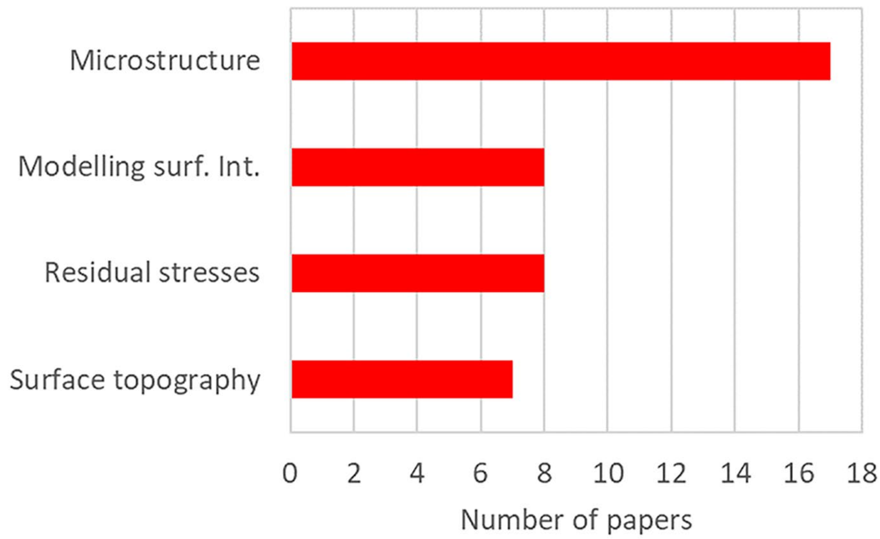

Fig. 10 Papers focusing on surface integrity in ESAFORM since 2007

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

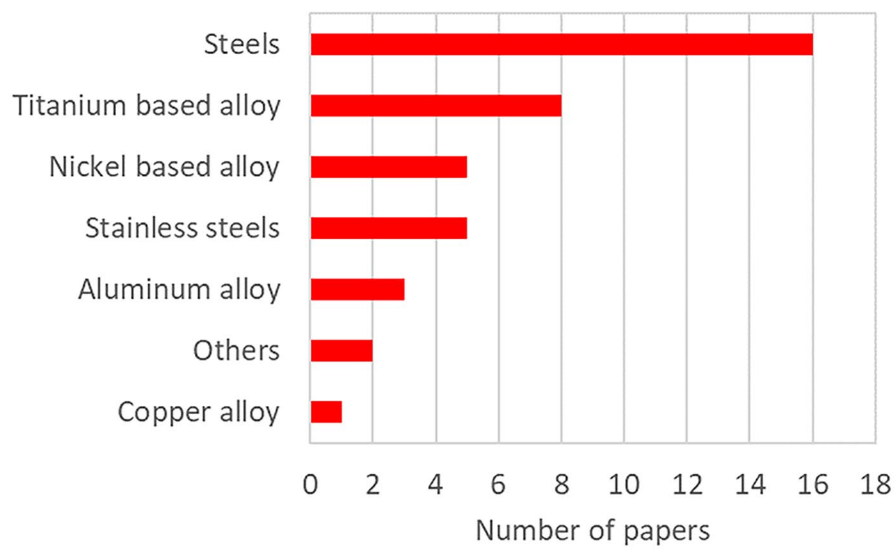

Fig. 11 Materials discussed on surface integrity in ESAFORM since 2007

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.

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)

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

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.

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Declarations

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

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