DEVELOPMENTS IN WEAR MAPS AS MACHINING OPTIMISATION TOOLS

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ABSTRACT

Tool wear maps can be a diagnostic instrument for failure analysis. This paper presents a summary of the recent developments of wear maps and experimental results from the milling of a Ti6Al4V benchmark component. This forms the foundation of understanding the cutting demands on the tools, in order to analyze the main wear mechanisms. Remedial actions are integrated via this understanding of the failure modes and related mechanisms. These maps present wear data in a graphical manner and are able to provide a more global picture of how materials behave during cutting. In tool wear maps there is a region where the rate of wear is at its lowest, called the safe zone. The presence of this safe zone suggests that it may be possible to select the machining parameters so that a machinist can operate with the lowest amount of tool wear, without compromising the level of productivity desired. Some thoughts on future directions for research in this area are also discussed.

1. INTRODUCTION

Since the 1980's there has been significant development in relation to the technical capabilities of cutting processes [1]. As illustrated in Figure 1, right at the core of all cutting processes is the understanding of the mechanisms of material removal (MR). Recent work [2,3] on the cutting edge engineering is showing us that significant benefits can be obtained by very careful analysis of the precise engagement conditions and of the precise mechanisms underlying material removal. Such an understanding allows us to assess the effectiveness of the energy conversion from the electrical power utilization at source to its conversion into useful work for the process [4].

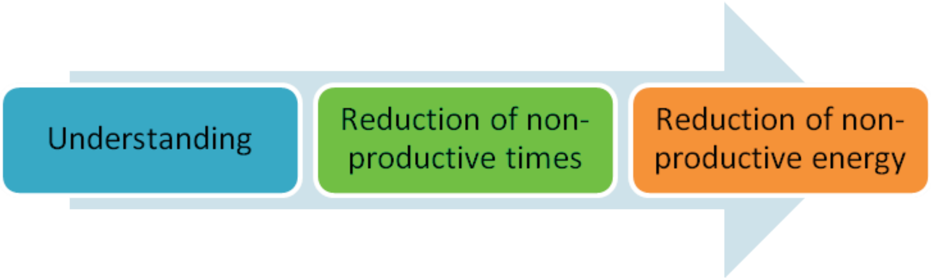


Figure 1: Towards evaluating material removal rates per kW of power required [5]

It is evident that an understanding of the operation is a fundamental requirement as input to future models. Thereby, we can consider non-productive energy and design our systems to reduce or eliminate it. This is a direction that needs a central location on the future roadmap of cutting technologies [5]. It is generally recognized that the cost of tool replacement represents a significant proportion of the total manufacturing cost [6]. A sizeable reduction in the total operating cost to the manufacturing industry could be achieved if cutting tools could be used for a longer period of time before being replaced. Productivity could also be increased as less time would be spent setting up these tools when they were replaced [4]. The primary cause of tool replacement is tool wear. To the designers and engineers, who have to make optimal decisions in situations where tribological considerations are significant, it is important for them to have ready access to information pertaining to the fundamental understanding of the wear processes of interest [1]. Wear maps can provide the appropriate information [7] for materials selection and choice of the suitable operating condition. There are a number of possible modes by which a cutting tool can fail. Expected degradation (gradual wear) of the cutting tool is the only accepted form within the machining industry.

Expected tool wear makes it possible to schedule tool replacements and to find the optimum cutting parameters, relative to the rate- and cost of production [8]. As illustrated in Figure 2 the wear maps can assist to choose the correct cutting parameters. The production planning process starts by analyzing the features of the component. Thereby, the machining strategy can be developed and the style of cutter be selected. Thereafter, initial cutting parameters could be selected that are used to simulate (using e.g. Delcam software) the cutting process of the component. Thus, the machinist can realize the total cutting time of the component and plan its schedule replacement tool times (SRT) accordingly. At the same time the machinist compare these parameters with the predicted tool life from tool wear maps. If the predicted tool life from the wear map is less that the SRT value, it will result in unplanned downtime. Therefore, it is essential for the machinist to ensure that the tool will cut for longer than the scheduled replacement time value.

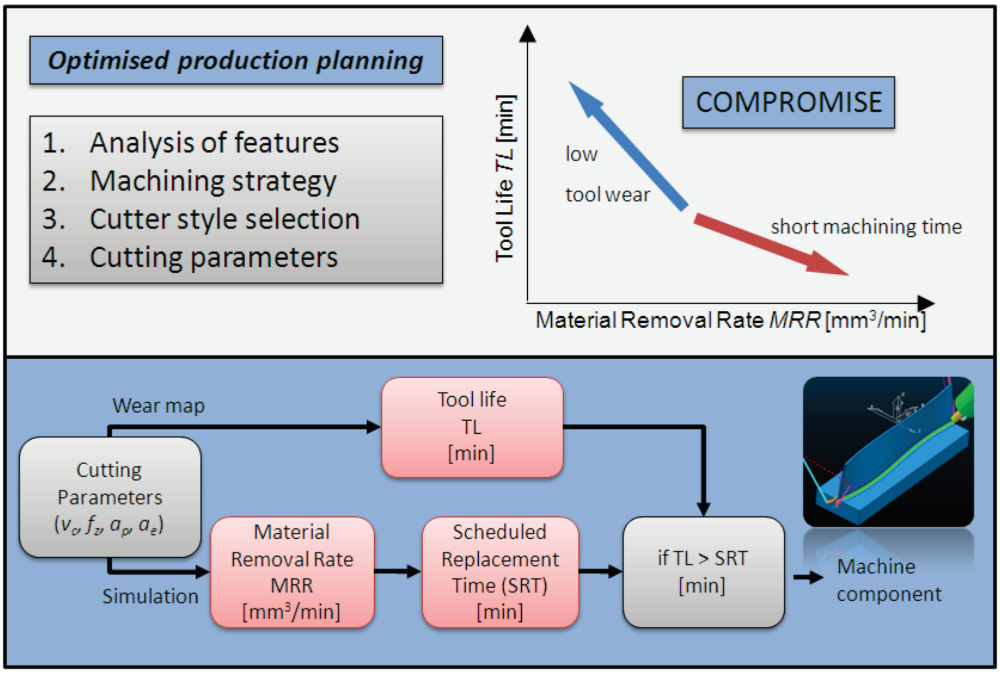


Figure 2: The production planning process for machining a component

As a result there will always be a compromise between tool life and the material removal rate (MRR). It was demonstrated that the judicious choice of machining conditions, made possible using appropriately constructed wear maps, could lead to the near-ideal situation of attaining a desirable productivity (MRR). Similar results were found by other researchers in the field [9].

2. DEVELOPMENT OF WEAR MAPS

One way to select the most suitable machining conditions is to examine the trends of tool wear with varying machining conditions [10,11]. Wear maps were taken a step further by Kendall [12], when a safe operating region was proposed for cutting tools by superimposing possible boundaries. It was suggested that as long as the machining parameters lay within this safe zone, the tools would not suffer catastrophic tool failure (failure before scheduled replacement time). Premature, catastrophic tool failure is the least desirable failure mode, because it is the most unpredictable, can be damaging to the work piece and cause costly downtime. This type of failure can be minimized through an understanding of the physical demands on the cutting tool and the effect of changing the operating conditions.

Quinto [13] constructed a tool wear map in terms of the two variables, namely cutting speed and normalized feed rate (the product of feed rate and depth of cut). This constructed tool wear map for turning operations is shown in Figure 3. These maps help to describe the global wear characteristics of cutting tools from machining operations. Wear maps representing the rates of tool wear in a two-dimensional space have been found to assist in such an optimisation process [11].

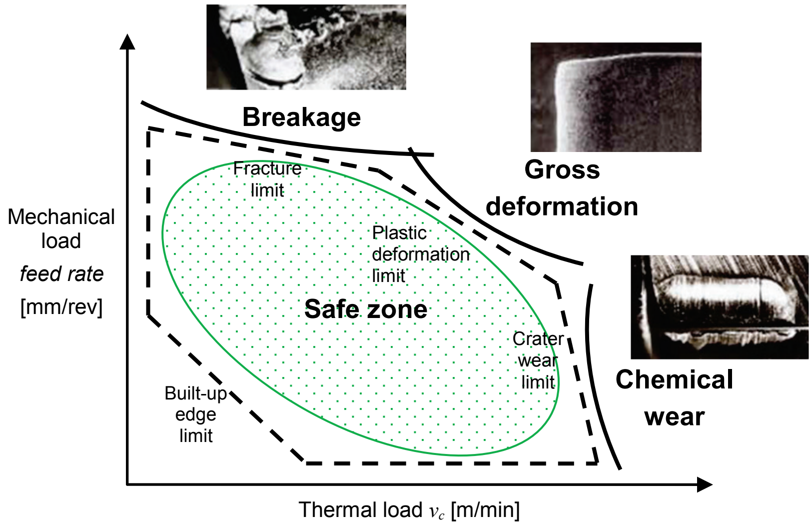


Figure 3: The failure mode diagram for a cutting tool material in machining [13]

This map illustrated above is derived from Kendall [12], the wear mechanism maps from Lim [9] and Trent's [14] machining charts. At this stage it was noted that further work is necessary to incorporate work piece related failure and remedial actions [1]. Figure 4 shows the developed wear map for milling (3D) operations and illustrates the way remedial actions are integrated. The positive correlation in terms of wear-rate trends obtained with other work piece materials suggests that this is a viable approach to achieve the objective of developing an integrated predictive system for tool wear in metal cutting [11].

The safe zone depicted in the failure mode diagram is a region of gradual wear associated with reliable performance [13]. Thermal activation refers to the breakdown caused by high temperature cycling of the cutting edge between the heating and cooling stages in milling. Chemical wear is therefore caused by a reaction between the tool and the work piece during cutting. The cutting edge strength is the property that resists the breakdown of the cutting edge due to the cutting impact. Breakage by means of fracture is found when the mechanical load exceeds the physical properties of the tool material [15].

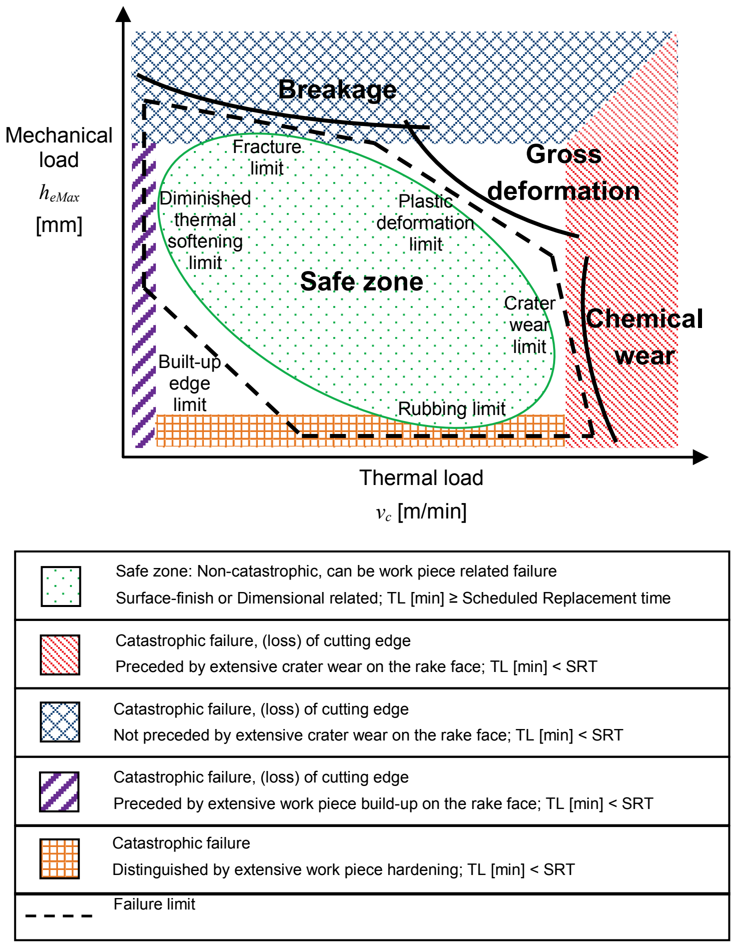


Figure 4: Tool wear map for milling as a function of cutting speed (v_c) and maximum un-deformed chip load (h_{eMax})

Tribo-chemical wear is a combination of chemical-mechanical wear; and may be considered a thermally activated process whereby the work piece material and tool material react in such a manner as to remove material from the tool on an atomic scale [15]. Abrasion wear is caused by the action of the sliding chips on the rake face of the tool, as well as by the friction phenomenon between the flank face of the cutting tool and work piece. Abrasion wear takes place primarily due to the hard grain orientations [1] in the work piece, which can act like hard inclusions in the work material; and is compounded by the part's hardness and strength properties. Figure 5 illustrates the remedial action process flow that was developed to support decision making for the machinist using the tool wear map.

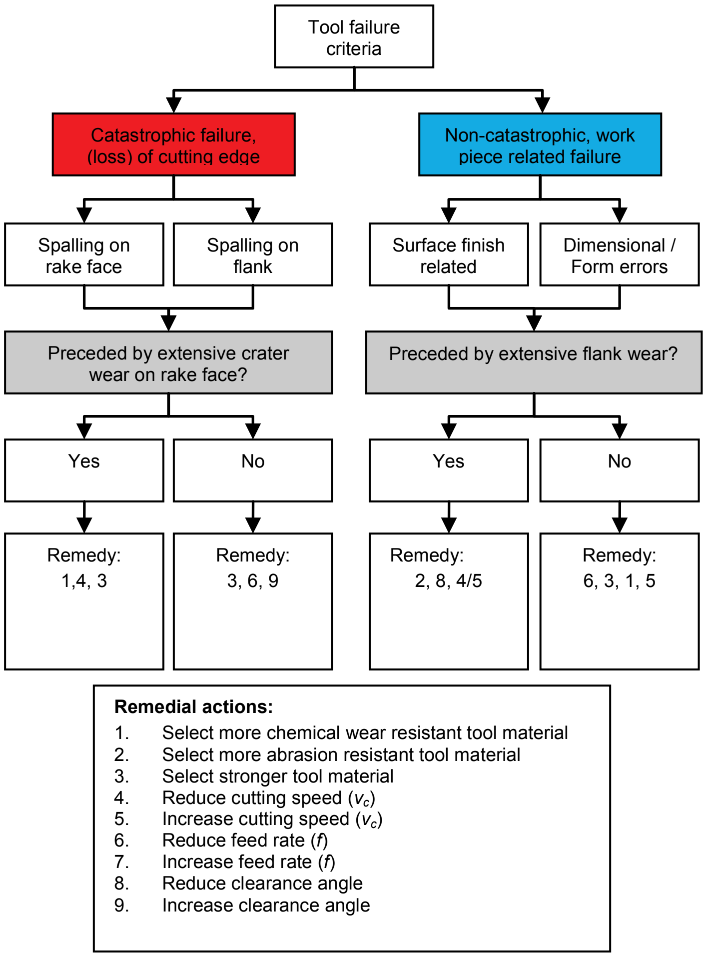
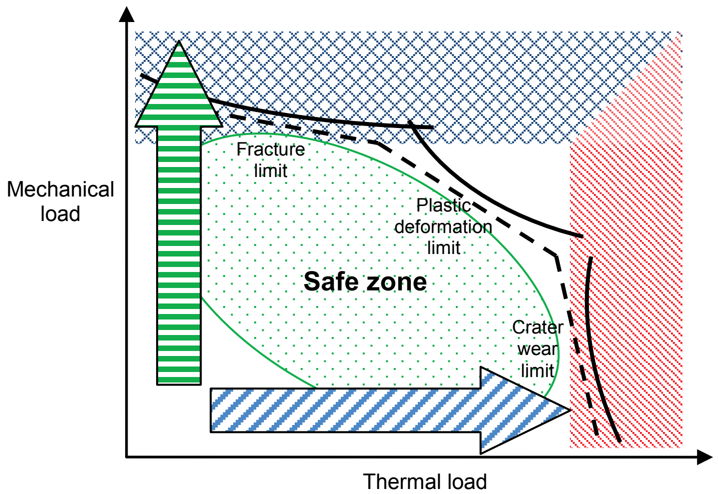


Figure 5: Remedial actions to different failures

Thereby, it is possible to compromise between the tool wear and the machining time relative to the material removal rate (MRR); and remedial actions could be considered to improve the process. Considering the different tool material needs according to this constructed map, Figure 6 illustrates the increasing need for tool toughness and mechanical strength, with an increase in the mechanical load. The figure also illustrates the increasing need for tribo-chemical wear resistant tool materials with an increase in the thermal load.



	Safe zone: Non-catastrophic, can be work piece related failure
	Higher possibility for chemical- and thermal wear (Thermal cracks, Thermal fatigue)
	Higher possibility for impact related wear (Chipping, Mechanical fatigue)
	Increasing need for tribo-chemical wear resistance and for hot hardness (Increase in the direction of the arrow)
	Increasing need for toughness and for mechanical strength (Increase in the direction of the arrow)

Figure 6: Illustration of the tool material property needs and the mechanisms under different physical demands (Arrows and markers are for concept explanation purposes only)

Independent of the tool material properties and tool geometry, there is a higher possibility for catastrophic tool failure by fracture with a relative high mechanical load. In contrast, there is a higher possibility for catastrophic tool failure, preceded by extensive crater wear, with a relative high thermal load. This current understanding of the physical demands on tool materials helps establish cutting conditions for new experimental tool entrants as it is possible to be aware of the effect of these parameters on the physical demands of the cutting tool.

3. MAPPING METHODOLOGY

Several broad steps need to be taken to construct the maps describing the wear characteristics of an operation.

Figure 7 describes the steps that need to be taken to develop a tool wear map. The pair of materials of interest, their mode of contact, the environment in which they are to interact in and lubrication condition should first be identified. Thereby, the additional complications brought about by the different complex wear mechanisms can be minimized. The lubrication strategy should be selected and the experiments conducted under normal atmospheric condition. Additional static interaction diffusion-couple experiments can help to study and understand the chemical interactions at different temperatures better.

Experimental data from background studies, literature and industry on wear rates and wear mechanisms pertaining to the conditions specified in the previous step should be gathered and studied. An economic viable SRT value (30 minutes) should be selected to group this data into catastrophic or non-catastrophic tool failure modes.

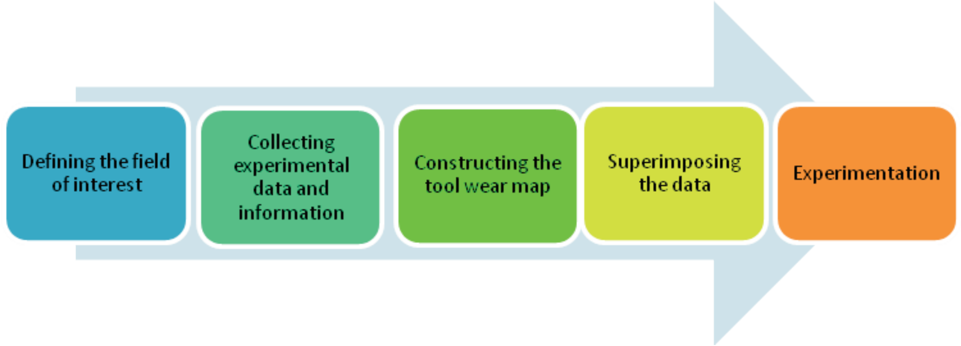


Figure 7: The steps to develop a tool wear map

The tool life (TL) can be examined through an extended Taylor model with boundary conditions found in literature. Mathematical models describing the wear behaviour for the selected conditions should be investigated. Wear data obtained from laboratory-type experiments, such as pin-on-disk should be stated in this phase. Various tool wear maps from literature should be considered.

It is possible to construct two- or three dimensional tool wear maps. The majority of these wear maps are of the two-dimensional type. The parameters used as axes for the two-dimensional maps should be decided on. The effect of the radial immersion (a_e) can be considered in the tool wear maps by constructing a wear map for both rough- and finish milling. It is desirable to select the ranges of these parameters as wide as possible. The collected wear data should then be introduced into this two-dimensional plane. The results should be classified into catastrophic- or non-catastrophic tool failure. Catastrophic define tool failure earlier than the SRT value, while non-catastrophic describes a longer tool life. The empirical wear maps can then be constructed by grouping the wear data according to the failure mode and mechanism of wear. The field of dominance of each mechanism should be identified using field boundaries. At this stage, the wear map is sufficiently informative and provides a summary of the tool wear behaviour. The work piece failure can then be superimposed onto the tool wear maps constructed, to understand the global failure boundaries. Remedial actions should also be considered and integrated into the tool wear maps. In order to check the validity of the map, carefully executed milling experiments should be carried out.

4. DEVELOPED TOOL WEAR MAPS

The wear map for turning (2D simulation operation) of steel with uncoated carbide tools is illustrated in Figure 8 [11]. The conventional definition of flank wear (V_b) was adopted. However, a more useful representation of the wear rates was found to be the dimensionless. Each point on the two-dimensional plane defined by the feed rate (f_n) and cutting speed (v_c) represents a particular machining condition, indicating the wear rate measured under that condition.

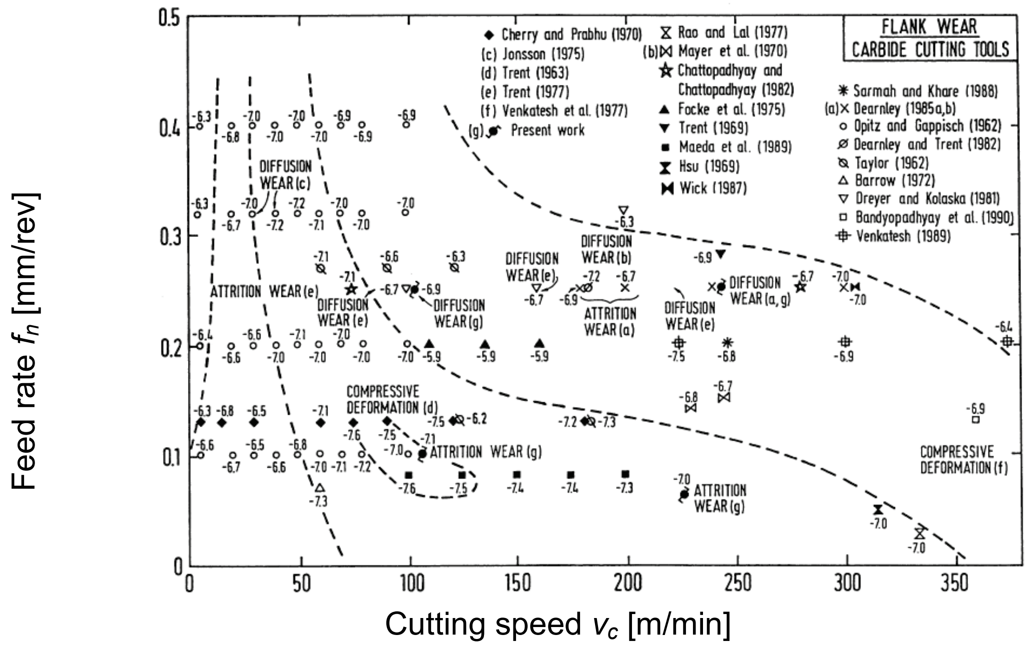


Figure 8: Map showing the rates of flank wear (V_b) of uncoated carbide tools during turning of steel. The numbers next to the points are $\log_{10}$(V_b/cutting distance) [11]

Each data point on this map represents a unique machining condition, with which is associated an experimentally measured rate of flank wear; the wear mechanisms observed at different machining conditions are also indicated. The dashed boundaries demarcate different regimes, within which wear rates of similar ranges in values are contained. This may be visualized more clearly in Figure 9 [11].

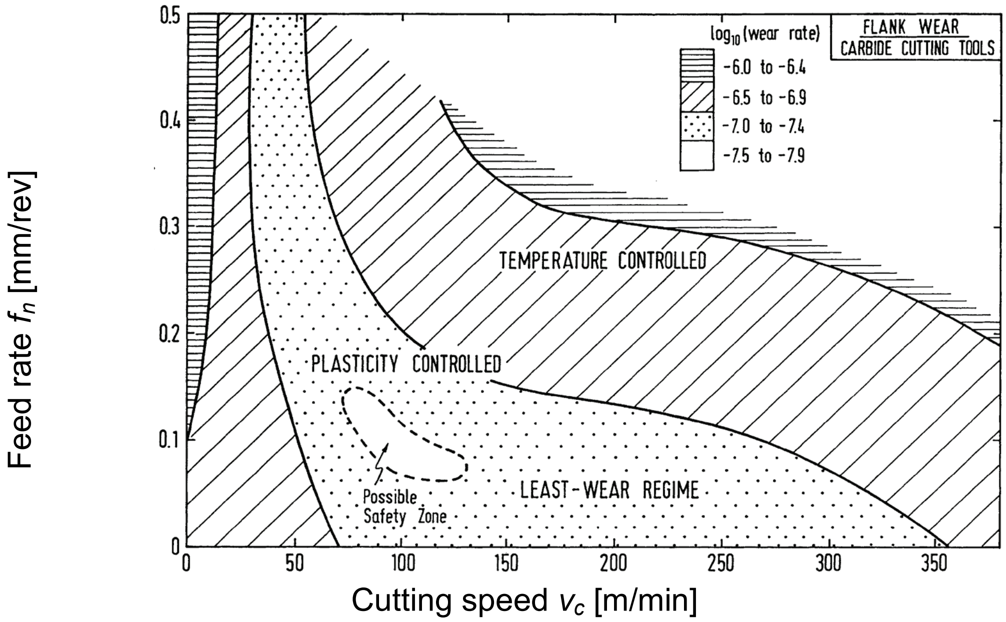


Figure 9: Map for flank wear of uncoated carbide tools (V_b) during turning of steel. The regions where the different ranges of wear rates are observed are shaded accordingly [11]

The boundaries have been re-plotted with all data points removed and the various regions appropriately shaded. In this map, a region where the wear rates are low is marked out. In the so called safety zone, the uncoated carbide tools would experience the lowest flank wear. The area with the next highest wear rates (-7.0 to -7.4) are known as the least-wear regime since wear rates here are only slightly higher than those in the safety zone. This regime covers a much wider area than the safety zone. Therefore, it is suggested that machinist should instead try to machine within the wider least-wear regime.

In milling (3D simulation operation) it was found that cutting speed (v_c) and maximum un-deformed chip load (h_{eMax}) played a critical role in determining the extent of wear on cutting tool materials [1]. These machining parameters (v_c and h_{eMax}) were chosen as the wear map's axes. According to our research [4] and tool suppliers [16] the tool life for the milling of Ti6Al4V should currently be at least 30 minutes (SRT) to ensure an economic viable solution. Therefore, if a cutting tool material withstands the cutting demands for longer, the cutting conditions define the safe operating zone. The coated carbide tools were analysed at conditions similar to that during high performance machining. The cutting speeds ranged from 40-100 m/min and chip loads from 0.1-0.4 mm in order to validate this superimposed map. Relatively high v_c and very high h_{eMax} were chosen for the tests with the carbide. Figure 10 illustrates the tool wear map for rough milling of Ti6Al4V with carbide cutting tools. The figure illustrates which cutting experiments failed catastrophically due to too high chip load (exceeding the fracture limit) and cutting speeds (exceeding the crater wear limit).

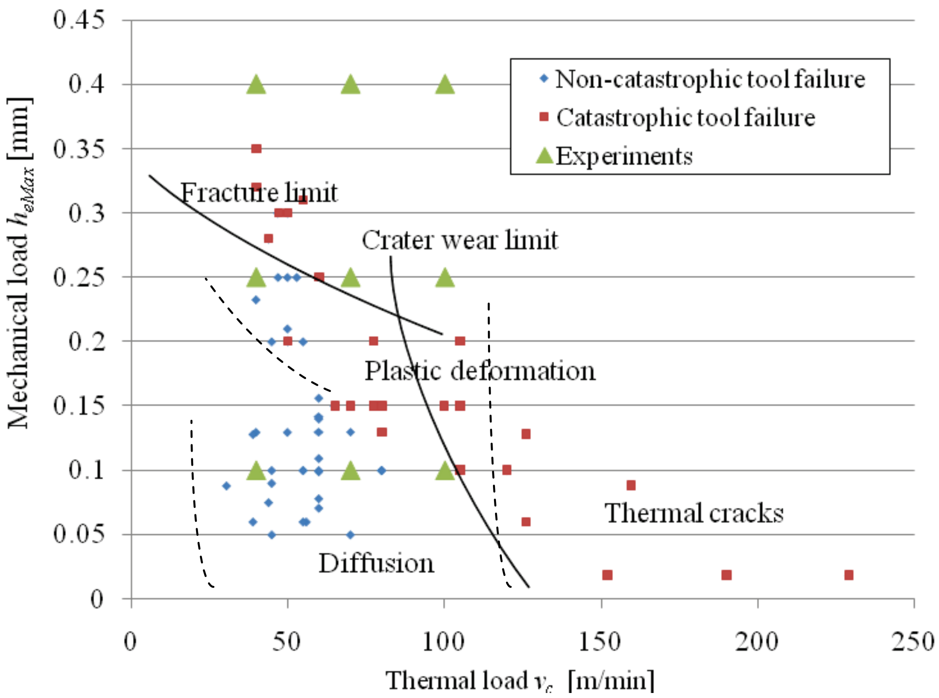


Figure 10: The constructed wear map for rough milling of Ti6Al4V with carbide tools

Thermal cracks were found for cutting speeds higher than 150 m/min. The carbides were found to plastically deform at $v_c \leq 60$ m/min with a relative high chip load. The stipple-lines indicate the start of the different type of wear mechanisms. The solid fracture- and crater wear limit lines were complemented in background studies [17]. The catastrophic tool failure points in the safe zone were taken into account, but were found to be the result of experimental tool materials and improper milling machines.

Finish milling of Ti6Al4V with polycrystalline diamond (PCD) shows promising results at v_c ranging from 175-200 m/min and h_{eMax} < 0.032 mm [4,18]. Cutting speeds of 300 m/min were found to cause work piece related failure (material burn) [1,4] The tool material was analysed at conditions similar to high-speed machining with v_c ranging from 100-300 m/min and h_{eMax} from 0.009-0.019 mm. The a_e was varied between 0.5-1 mm. Figure 11 shows the constructed tool wear map for finish milling of Ti6Al4V with PCD cutting tools. The figure also illustrates the experimental parameters for this study with the fine grain PCD material.

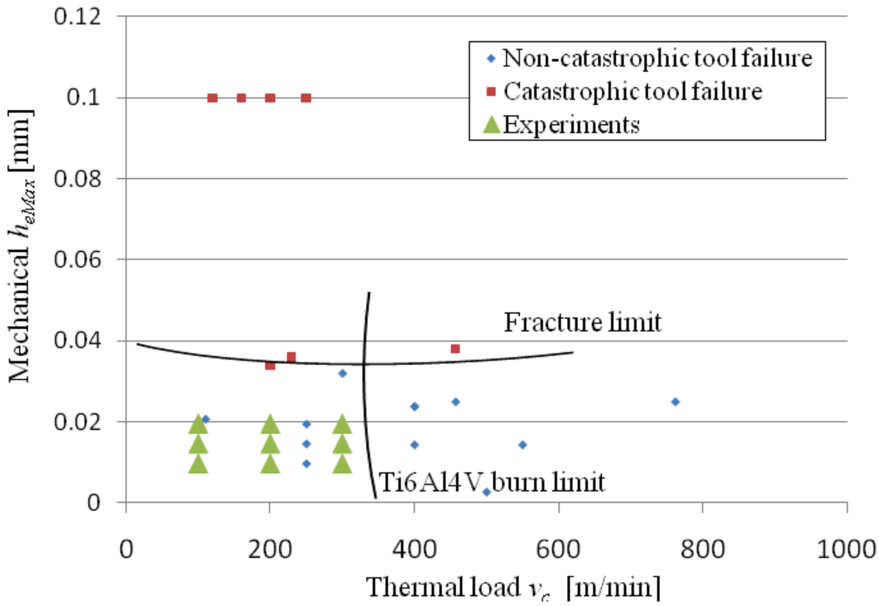


Figure 11: The constructed wear map for finish milling of Ti6Al4V with PCD tools

None of the PCD cutting tools failed catastrophically (TL<30 min), but whether it is an economic viable solution still needs to be considered. As a complementary perspective these results proved that the cutting speeds (thermal load) for PCD tools in finish milling conditions are limited to the cutting range 200-300 m/min under a low mechanical loading of h_{eMax}=0.019 mm.

5. TOOL WEAR MAPS IN PRACTISE

Titanium alloys are used for high value components, not only components used in an aircraft's frame and engine, but also in the biomedical field. Workshops able of sustained growth will migrate toward higher-end work, meaning that a growing percentage of machining shops will encounter titanium alloys. Therefore, attention to milling titanium is worth attention in order to achieve higher productivity, when raising the cutting speed is not an option. In a collaborative research study between the academia and aerospace industry a benchmark part was selected. This part helped to understand the tool demands from the Ti6Al4V work piece and to improve the milling strategies used currently in industry. This benchmark part illustrated in Figure 12 has an "S" shaped geometry and is thin walled. It has other geometry aspects commonly associated with aerospace components, like undercuts and compound angels. Using the wear characterization map illustrated in Figure 10 and the strategy shown in Figure 2, improved parameters and milling strategies were realised for the cutting of the component. The used tools were examined with an optical microscope and scanning electron microscope (SEM) imaging and were characterized so as to categorize them into a failure region. Thus, remedial actions could be considered to improve the process.

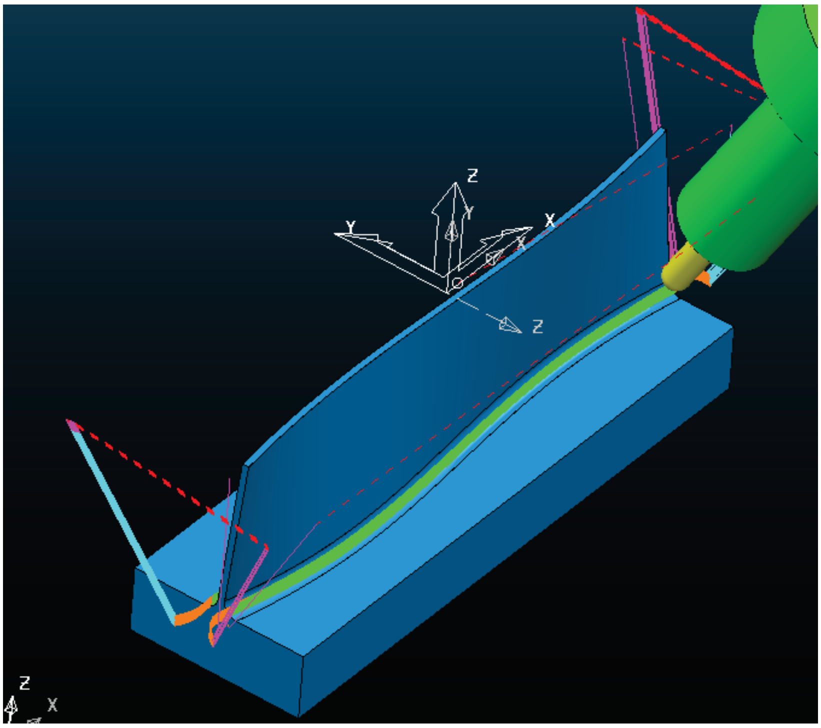


Figure 12: Demonstrator 1: "S" shaped geometry thin walled component

Comparing the different machining times a significant difference can be seen between the 1^{st} and 2^{nd} opportunity's cutting times. This is largely due to revision of cutting tools and cutting strategies using the wear map. An increase in both the cutting speed and feed rate could be realized relative to the specific SRT values using the strategy illustrated in Figure 2. Both the roughing and the semi-finishing for this benchmark component can now be completed in less than 20 minutes.

	CUTTING CYCLE	1^{st} Simulation [min]	2^{nd} Simulation [min]	1^{st} Cutting [min]	2^{nd} Cutting [min]	Material Removed [cm^3]	Material Removed [%]
1	1^{st} Roughing	30	4.1	7.09	7.09	283.898	61.01
2	Semi Finishing	20	3.53	12.25	12.25	141.858	30.49
3	Flat Area Finishing	5	1.13	2.32	2.32	1.665	0.357
4	Side Wall Finishing	180	6.47	12.16	12.16	33.957	7.30
5	Corner Fillet Roughing	N/A	N/A	49.02	9.4	3.608	0.775
6	Corner Fillet Finishing	1	6.35	30.96		0.348	0.074
7	Blade Final Finish	N/A	N/A	2.56	2.56	0	0
	Total cutting time	***236***	***21.5***	***116.36***	***45.78***	***465.334***	***100***

Table 1: Machine time summary

Using a five axis machining strategy the roughing and finishing of the radius sections could be done in one strategy. A smooth cutting motion was noted and no visible tool wear could be seen on the cutting tool with the 2nd opportunity's cutting parameters. This brings the total machining time for the component down to 45.78 minutes compared to the previously achieved 116.36 minutes. This is a massive saving in titanium machining time. The first simulation time was very high, but was significantly reduced for the second simulation, due to the use of totally different cutting tools and the wear map strategies.

6. CONCLUSION

Wear maps are useful to designers and engineers when they have to make engineering decisions where wear is one of the major considerations. It can also play the role of a diagnostic tool during failure analysis. Wear maps are slowly gaining acceptance as a user-friendly approach to the presentation of wear-related information. This can be seen from the increasing number of maps presented during recent years. Notwithstanding these achievements, a greater effort could be channelled into the construction of new maps for different operations and materials. Tool wear maps should be designed to serve primarily as diagnostic tools and with the aim to serve the end-users. Future wear maps should include SRT dependant maps. It can also be useful simulate the tool life using the different tool wear models.

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