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Application of a water-based non-oil lubricant in turning for hybrid manufacturing

Felipe Rahn[1,3], Alexandre Gilbin[1], Michaël Fontaine[1,*], Xavier Roizard[1], Jean-Marie Melot[2,3], Fabrice Lallemand[2,3]

[1]*FEMTO-ST Institute (UMR 6174), Dept. of Applied Mechanics, University Bourgogne Franche-Comté - UBFC (UFC/ENSMM/UTBM), Besançon, France*

[2]*UTINAM Institute (UMR 6213), SRS team, University Bourgogne Franche-Comté - UBFC (UFC), Besançon, France / AFULudine, Dole, France*

[3]*AFULudine, Dole, France*

**corresponding author: michael.fontaine@ens2m.fr*

Abstract: In recent years, the hybrid additive and subtractive processes are gaining increasingly importance in the industry. By combining the advantages of both methods, this new manufacturing strategy allows the creation of much more complex pieces with a fine surface finish, which was quite difficult to obtain with the conventional methods. However, some problems are still related to this association of processes. One of them concerns the use of cutting fluids, important to optimize the machining part, but that can strongly affect the additive part by generating pores in the laser metal deposition. Toward sustainable manufacturing, the present work studies the performance of a new ecological cutting fluid that dries by itself, eliminating the need for a cleaning step between the machining and the laser metal deposition. This study is carried out by comparing the machining performance of this new cutting fluid with others more widely used in the market. It was found that machining forces and surface roughness were not very affected by the change of the lubrication mode, while the tool wear showed a significant difference between the dry and the lubricated cases. Considering that the performance of all the cutting fluids was very close, it was concluded that the new lubricant has great potential of application, since it is ecologically advantageous, non-harmful to the operator and does not need a degreasing step before melting operations.

Keywords: Turning; Cutting fluids; 316L stainless steel; Sustainable machining; Surfaces Cleaning; Hybrid manufacturing

1. INTRODUCTION

As customers and applications become increasingly demanding, new manufacturing methods also emerge to adapt to this new reality. One of the great innovations of the market in recent years has been the development and expansion of hybrid manufacturing machines, able to reduce production time and create customized products [1]. By combining additive (laser metal deposition, LMD) and subtractive (machining) processes, this new method allows the manufacturing of much more complex pieces with a high productivity, but still with a fine surface finish. It means that the advantages of both types of manufacturing are combined in order to optimize the whole process, as illustrated by Figure 1. The 'stair effect', generated by the deposition of powder or wire layers in the LMD-process, is eliminated by machining and finishing the workpiece [2].

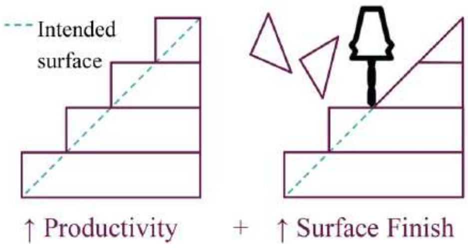

Figure 1 - Combination of the advantages of additive and subtractive manufacturing [3]

However, some challenges are still related to this combination of operations, and one of them is the use of cutting fluids, important to the machining optimization, but which can disrupt the additive part by aggravating one of its weaknesses: the porosity formation.

Without considering the presence of a lubricant, [4] studied the porosity effect on Ni-based coatings deposited through LMD and showed that it can contribute to the brittle fracture and reduce the strength of the structure. According to Ng et al. [5], the pores are mainly originated by gas bubbles that are trapped with the powder stream.

Now considering the presence of a cutting fluid, this tendency to pores formation increases even more. Zhong et al. [6] studied the influence of several parameters, such as drying treatment of the powder, laser power and nominal powder particle size, on the porosity of laser deposited single tracks in high-deposition rate LMD. They showed that the drying treatment has a significant influence on the resulting porosity and that the use of dried powder can reduce it considerably.

In hybrid machines, as additive and subtractive processes are intercalated, the piece must usually be cleaned before the LMD to avoid this pore formation. Alshaer et al. [7] proposed a method based on a nanosecond pulsed fiber laser to clean the substrate before the powder deposition and showed that this cleaning stage can significantly reduce the final porosity. Barckhoff [8] also correlated the presence of a cutting fluid with the introduction of gas bubbles, saying that any lubricant on the surface should be removed before the additive part.

Cortina et al. [9] carried out a quantitative study of the influence of a cutting fluid on the LMD. They showed that when lubricants with a low concentration of oil (5% for the studied one, Houghton HOCUT B-750) are employed, there is practically no need of a cleaning step before the LMD. However, the higher the concentration of oil, the higher the amount of pores. For concentrations higher than 10%, they showed that the cleaning stage between machining and LMD is indispensable. If this cleaning is not done, there will be generated a mixture between the cutting fluid and the powder particles, which will make the layer-by-layer deposition unstable. Finally, they showed that an appropriate cleaning stage is able to completely avoid the porosity for the typical oil concentrations in machining (5-10%).

Hence, it is concluded that the presence of any cutting fluid remaining from the machining is strongly related with the pore formation in the LMD process. A cleaning step is an option to remove this lubricant, but it implies the introduction of a cleaning stage, which increases the cost and the total process time. Thinking about that, the present research work aims to evaluate the performance of a new cutting fluid created by the French company AFULudine. This new lubricant, called AFO, solves the mentioned problem, because its formulation causes it to evaporate quickly, so that there is no need of a cleaning step, since it dries by itself. Besides of this, AFO still presents other great advantages compared to the others: it has already been certified as environmentally friendly and non-harmful to the operator.

All these factors justify a study of the application of this new cutting fluid in hybrid manufacturing. Therefore, the idea of this work is to compare AFO to other most commonly used lubricants. It is made by analyzing their performances in machining, since it is where the fluid plays its main role. Two groups of turning tests are performed to compare the cutting fluids. In the first one, based on the work of Nur et al. [10], straight turning is carried out in different conditions by varying the cutting parameters, i.e. cutting speed, feed and depth of cut. The resulting parameters analyzed are the machining forces, surface roughness and chip velocity. The second group consists of accelerated tool-life tests, in which the same tool is used during 15 minutes and its final wear is analyzed. An overall experimental assessment makes it possible to compare all the cutting fluids according to the factors that are important for the intended application.

2. A NEW GENERATION OF LUBRICANTS

Thanks to a fruitful collaboration between different academic and industrial research entities, a new green lubricant solution AFULudine has been developed for manufacturing operations in substitution to the usual mineral oils, with the idea and the wish to combine different essential properties such as a low environmental impact and ease-of-use according to the market needs and the more and more restrictive environmental legislation (e.g. REACH). Based on the Self-Assembled-Monolayer (SAM) principle and on a high control of the chemical reaction between the solution and the substrate (grafting of molecules onto the surface), this new generation of lubricants offers an efficient technical answer for improving manufacturing processes.

The development of the proposed solution is based on the control of the chemical reaction between specific active molecules and metallic oxidized substrates such as stainless steels. It ensures surface functionalization by using organic molecular assemblies like Ulman et al. previously did [11], and more especially by using alkylphosphonic acid molecules. These molecules are well-known to act as a protective layers formed by chemical reaction with the metal surface due to a fairly high level of chemical activity [12]. Raman et al [13] studied their ability to create a Self-Assembled-Monolayer (SAM) on the surface of an oxidized austenitic stainless steel (316L). In more recent studies [14, 15, 16, 17], significant improvement of the tribological behaviour of different substrates (copper, titanium, stainless steels) was demonstrated and assigned to alkylphosphonic acids molecules used as nano-size liquid additives in lubricant, highlighting more especially the formation of low-friction tribofilm during sliding, responsible for the surface protection. Such active molecules are the very essence of the AFULudine solution, which constitutes today a more environmentally friendly lubrication solution than the standard petrochemical lubricants.

The AFULudine solution was patented [18] and different products were developed, tested and validated for industrial applications such as punching and stamping of stainless steels [19]. Up to now, based on the use of alkylphosphonic acids as organic friction modifiers, the products haves been thought to ensure an industrial easy of use in these fields thanks to a hydro-alcoholic solvent. But in the case of machining, this highly voluble and flammable type of solvent is not adapted, and functions as heat absorption and continue regeneration of functionalized contact have to be ensured, even in very confined zones. A new version of this product is currently developed by using a water basis. The idea of the presented work is then to compare the efficiency of this new concept in comparison with commercial lubricants dedicated to machining, with the purpose to propose a new solution which is ecologically advantageous, non-harmful to the operator and which needs not a degreasing step before melting operations.

3. MATERIALS AND METHODS

All the experimental tests were performed on a Doosan Lynx 220Y, a 4-axis CNC lathe with a maximum spindle motor power of 15 kW and a maximum spindle speed of 6000 rpm.

The workpieces were made from AISI 316L, an austenitic stainless steel widely used in additive manufacturing. **Erreur ! Source du renvoi introuvable.** shows the material composition.

Table 1 – Composition of AISI 16L workpiece material

Grade		C	Mn	Si	P
316L	Min	–	–	–	–
	Max	0.03	2.0	0.75	0.045

	S	Cr	Mo	Ni	N
Min	–	16.0	2.00	10.0	–
Max	0.03	18.0	3.00	14.0	0.10

The turning inserts used were made from tungsten carbide and coated with three layers of TiCN, Al_2O_3 and TiCN. The tools are designated as ISO CCMT09T304 and ISO CCMT09T308, with corner radius of 0.4 and 0.8 mm, respectively. The coating thickness and the cutting edge radius, measured with a numerical microscope, were, respectively, of about 5 and 50 µm.

Based on the material and the tool manufacturer's recommendations, the turning conditions for the first group of tests (straight turning in finishing and roughing) were defined as shown in Table 1. For each operation, there are then nine combinations of parameters, and all of them are doubled to verify the repeatability of the results.

Table 1 - Cutting conditions in straight turning

	Cutting speed Vc [m/min]	Feed rate f [mm/rev]	Depth of cut d [mm]
Finishing tests	120 - 200 - 300	0.10 - 0.15 - 0.20	0.5
Roughing tests	120 - 200 - 300	0.10 - 0.20 - 0.40	1

For the tool-life tests, based on the respective ISO standard [20], it was decided to work with a cutting speed of 200 m/min, a feed of 0.1 mm/rev and a depth of cut of 1 mm.

The machining forces were recorded by a dynamometer (KISTLER 9129AEO) connected to a multichannel amplifier (KISTLER 5070) in order to turn the dynamometer output signal into readable data. All the three components were studied, but in order not to overload this article, only the results for the cutting force, the most important between them, will be detailed. In any case, the results follow the same trends in all three directions.

The surface roughness was measured with a surface profilometer over a length of 10 mm of the machined workpiece. The parameter chosen to compare the cutting fluids was Ra, the average roughness.

In order to obtain the chip velocities, the chip thickness were measured after the tests with a micrometer. Based on the Figure 2 and on the fact that the uncut chip thickness *h* is equal to the feed rate *f*, the conservation of matter gives $Vc\ .\ f = Vchip\ .\ h'$, from which the chip velocity *Vchip* can be found.

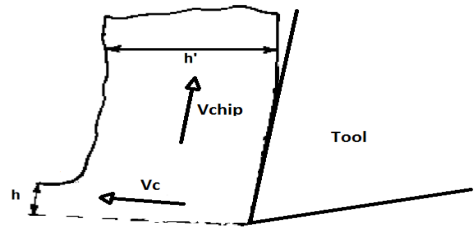

Figure 2 - Chip formation

Finally, the tool wear is analyzed using a numerical microscope (KEYENCE VH-ZST) whose amplification goes from 20 to 2000x. Following the ISO standard, the criteria Vb, the flank wear, is used to evaluate the tool wear.

Aiming to situate the AFO's performance, the following lubrication modes were employed:

- Dry machining, in order to get the reference of the worst case in machining
- Straight oil (Castrol CARECUT ES 2), in order to get the reference of the best case in machining, even if it is not a good solution for hybrid manufacturing
- Soluble oil (Jeffacool Poly-Shape), with an oil concentration of 5%, one of the lubricants currently recommended for hybrid manufacturing
- AFO, the new ecological lubricant, based on active molecules dissolved in water (7% concentration)

4. RESULTS AND DISCUSSION

This section presents the results obtained after all the tests and the analyzes with all the mentioned cutting fluids. Firstly, a good repeatability was verified for the doubled tests – the difference was less than 10% for all the cases. Besides, it can be observed in Figure 3 (for the finishing in the dry machining case, as an example) that the cutting parameters follow the expected trends: the cutting speed has no great influence on the forces and surface roughness, while a variation in the feed generates a visible change in these resulting parameters. This is in accordance with the results obtained in similar tests carried out by Nur et al. [10].

After doing this analysis for all fluids and noticing the same tendency, it was decided to work only with the average values for each feed, disregarding the influence of the cutting speed. By proceeding in this way, Figures 4 to 6 show the results for the analyzed parameters.

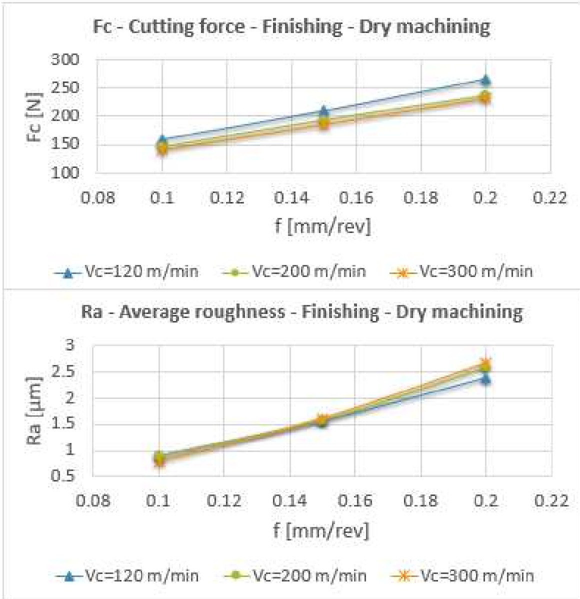

Figure 3 - Influence of the cutting parameters on the results for the dry machining case

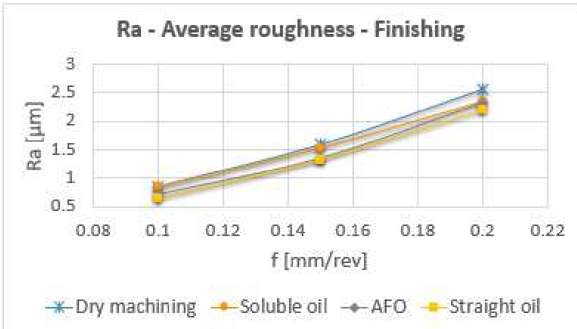

Figure 4 - Surface roughness comparison

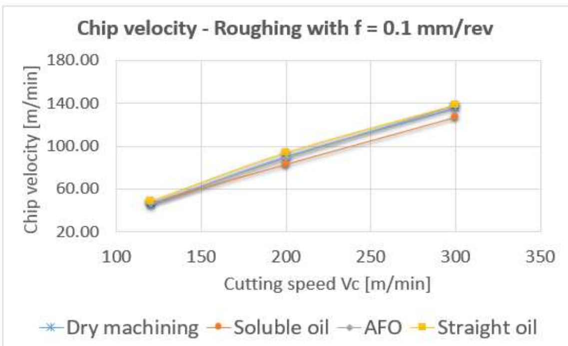

Figure 5 - Chip velocity comparison

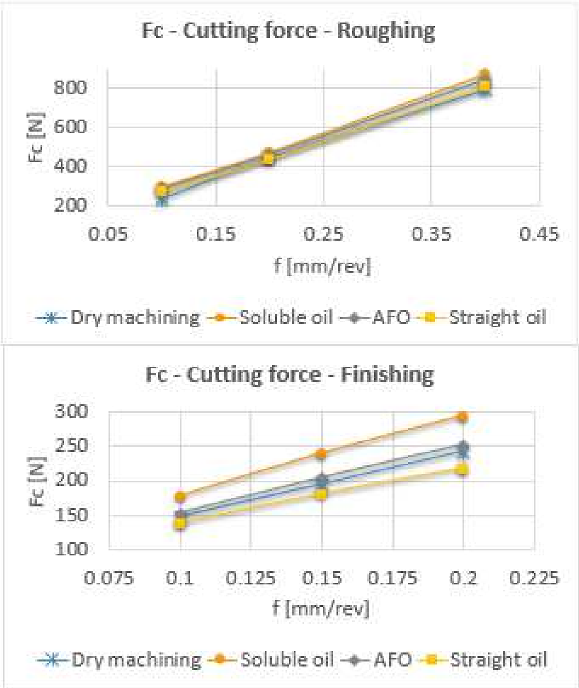

Figure 6 - Cutting forces comparison

As it can be observed, the differences between the results are not so significant (exception made for the soluble oil in finishing). For the surface roughness, the expected trends can be effectively verified, with the straight oil having the best performance and the dry machining case the worst. However, a more notable difference was expected for all the parameters, at least between the dry and the lubricated cases. At high cutting speed conditions (400, 600 and 750 m/min), the differences were even smaller, as shown by Figure 7.

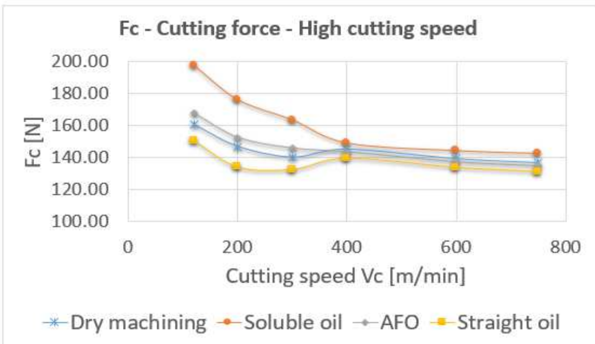

Figure 7 - Cutting forces at high cutting speed

This result leads to the conclusion that the chosen tool is very well suited to the range of tests and that the friction effects (reduced by the cutting fluids) are very small compared to the forces to remove the material. Because of this, a change of the cutting fluid does not affect the overall result so noticeably.

As these tests did not present discriminant results (which is also a quite interesting information), it was decided to follow the study with tool-life tests, since the tool wear is a parameter on which it is known that the cutting fluid has an important influence. Figure 8 shows the tools wear images obtained after 15 minutes of machining with each one. Only with the images, it is already possible to notice that the dry machining case presents a much more pronounced wear. The Figures 9 and 10 prove this by comparing, respectively, the flank wear value Vb and the final average roughness Ra.

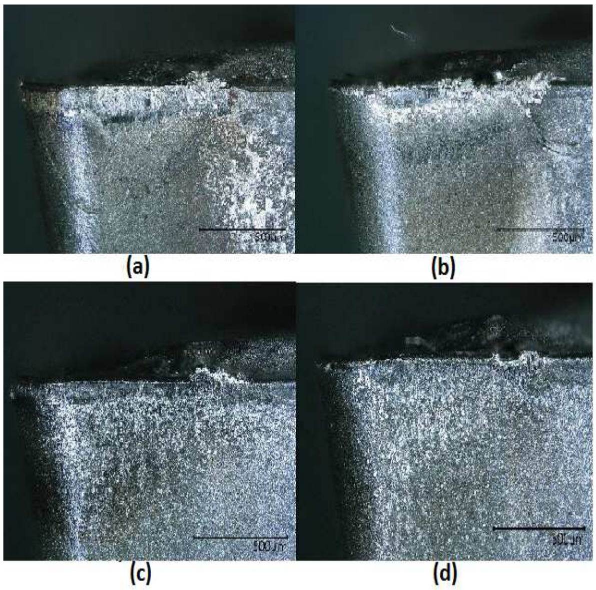

Figure 8 - Flank wear for: (a) Dry machining; (b) Straight oil; (c) AFO; (d) Soluble oil

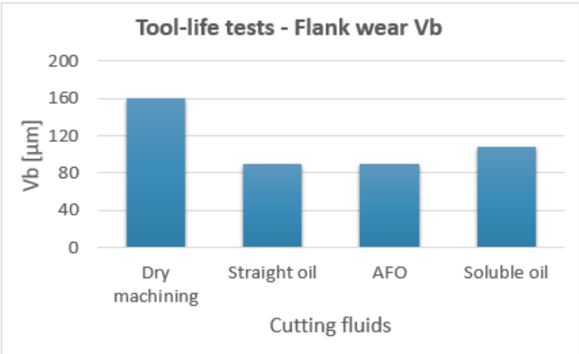

Figure 9 - Comparison of the flank wear Vb

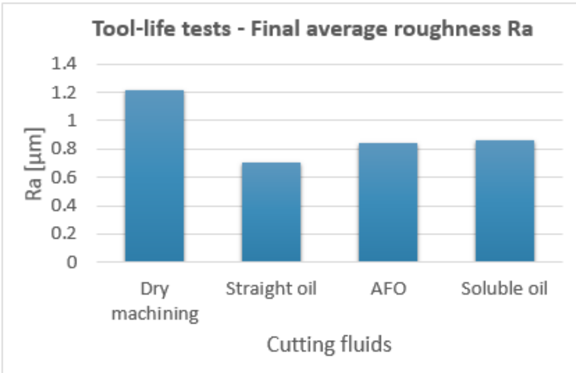

Figure 10 - Comparison of the final average roughness Ra

5. CONCLUSIONS

In the present work, a comparison between the machining performances of some cutting fluids was carried out. The main goal was to study a new application for the lubricant AFO, developed by the company AFULudine, in hybrid additive and subtractive processes, as it presents the advantage of drying by itself, not requiring a degreasing step between the operations. Various machining tests were performed in order to situate the AFO's performance in relation to some other lubrication modes and some conclusions can be drawn from the results obtained:

(1) It was found that for the initial cutting parameters chosen for straight turning, the results were not greatly influenced by the lubrication mode, even considering the dry machining case. As explained, it means that the tool insert used was very well adapted to the tests conditions and that the friction effects, reduced by the use of a lubricant, did not have a great influence on the global result compared to the forces to cut the material.

(2) On the other side, as expected, the tool-life tests results showed a clear difference between the dry and the lubricated cases, proving that the use of a cutting fluid significantly increases the tool life. Considering the three cutting fluids, the flank wear Vb presented similar values for all of them, with a slight advantage toward AFO and the straight oil.

(3) Considering that the turning performances are quite similar, other parameters can be analyzed in order to choose the best cutting fluid to apply in hybrid manufacturing machines. Figure 11 shows some important parameters to the intended application and the grades given by the work team to each lubrication mode.

- The criterion "machining performance" is justified by the results of the tests presented previously. The straight oil is the reference, the dry case is the worst one and AFO and the soluble oil are close to the high level.
- The "environment" criterion takes into account the environmental risks associated with the elimination of the fluids. The dry case and the AFO received the grade 4, knowing that there is still a consumption of material for the dry machining case (the tools wear faster) and of water to produce the AFO solution. There is not a perfect solution, but these two are the best in that sense. On the other hand, straight oil and soluble oil have great problems related to the contamination of soil, water and the atmosphere.

- The "operator" criterion concerns the harmfulness of cutting fluids for people who come into contact with them. Again, the maximum score is given for the dry machining case and for AFO, already certified as not harmful to the operator. On the other hand, the straight oil and the soluble oil require additional precautions, because they can cause problems like cutaneous pathologies or even cancers.
- Finally, the "cleaning" criterion is linked to the specific application of the project: the hybrid manufacturing. As already explained, the AFO lubricant does not require a degreasing step after machining, it dries by itself, which is quite interesting for the process. If one of the oils is used, the part must be cleaned after each machining to prevent the lubricants from disturbing the additive part.

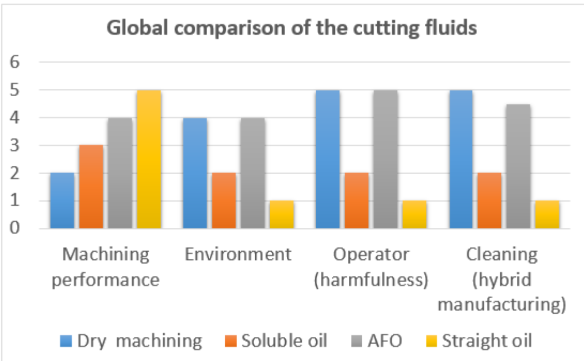

Figure 11 - Global comparison

As it can be seen, the AFO lubricant is very well situated in a general context. It is important to note that for now this conclusion cannot be generalized to all the machining conditions. Some other tests must be carried out to confirm if these trends are maintained using other cutting parameters and performing other operations (milling and drilling, for example). However, the present results are already a promising indication that the lubricant AFO can be an interesting option to the application in hybrid manufacturing.

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This work was carried out within the Manufacturing 21 working group, which gathers about 20 French research laboratories. The topics covered are the modelling of the manufacturing process, virtual machining, and the emergence of new manufacturing methods.

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