Current Status and Issues of Eco-Machining

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Environmentally-friendly technologies have been developed for manufacturing processes to reduce burden to the environment. Especially in machining, the measures called "Eco-Machining" were progressed; these were reduction of cutting fluid usage, use of energy-saving devices and improvement on tools. There was, however, a low estimation left on the reduction of cutting fluid usage, where the existing production equipment was used for the eco-machining, because many malfunctions occurred in these machines. Improvement must be made on handling of cutting chips in order to realize the environmentally-friendly machining.

Key Words: *eco-machining, cutting fluid, energy-saving, tool, cutting chips*

1. Introduction

At the beginning of the year, I was asked to write a paper on the theme of "Eco-machining, Tribology, or another topic of choice" and, with no small amount of hesitation, I accepted. I believe one of the reasons I received this request was because I had been the chief examiner of the workshop "Eco-machining & Tribology", proposed by members of the Japanese Society of Tribologists. However, in reality, this workshop had not been in session for sometime, and in March of this year, dissolved upon integration with another workshop, "Machine Tool Tribology." The main reason why the workshop was not held was due to the difficulty of finding contributors.

2. Shift in CO_2 Emissions

Figures 1 and **2** are sourced from reference material 1 (Transitional changes in emissions amount by CO_2 sector)[1)] used in the 9th Carbon Planning Study Group session (Mar. 9 2018) hosted by Japan's Ministry of the Environment. Carbon planning is an initiative to reduce CO_2 emissions through carbon tax, etc. and it is vexing to think that professors in literature sit around in a well air-conditioned room discussing such a topic at length. **Figure 1** shows the sectors where a power plant's power (CO_2 emissions, etc.) is ultimately consumed, and it is evident that there has been a remarkable increase in CO_2 emissions by the "Business and Other Sector" over the past 25 years, with the majority of this comprising of electric power. The "Household Sector" shows the second largest increase (personal cars are included in the "Transportation Sector") and here as well, two-thirds of the total comprises of electric power. Ultimately, as seen in **Fig. 2**, which shows the sources of CO_2 emissions, it is apparent that in the Energy Conversion Sector, represented by power plants, etc., CO_2 emissions have been increasing at a constant rate. The reason for this is because it is now taken for granted that electric power will be used to cover the air conditioning in our homes and offices in order to create a comfortable environment. Thinking back, I remember that twenty years ago, there was no air conditioning in the university lecture halls or labs, and students had to bear the heat during graduate school entrance exams held in summer to continue writing answers all day long -this was the borderline between victory and defeat. Moreover, I personally can recall on extremely hot days, when I simply couldn't stand the thought of working even in shorts, how my colleague and I would go to eat ayu sweetfish at the "yana" ("fishing weir"). Meanwhile, CO_2 emissions by the Transportation Sector, which is often the target of ruthless public scrutiny, show a downward trend over the past 20 years. The number of cars, however, has increased over this period of time, therefore it is clear that fuel economy improvements are contributing to this reduction. The CO_2 emissions of the Industrial Sector, which involves eco-machining, have also decreased consistently since 1990, with the difference in the CO_2 emissions shown by **Fig. 1** and **Fig. 2** being primarily due to electric power consumption, and it is clear that this electric power consumption has also fallen consistently. It is the way

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of Japanese industry to wring out an already somewhat dry cloth, and eco-machining is the manifestation of this spirit. The reason why we were unable to find contributors for the workshop I mentioned at the outset, is believed to be because the use of eco-machining is expanding in production sites where application of such technology is possible, and it is difficult to find an angle of eco-machining that serves as a new research theme.

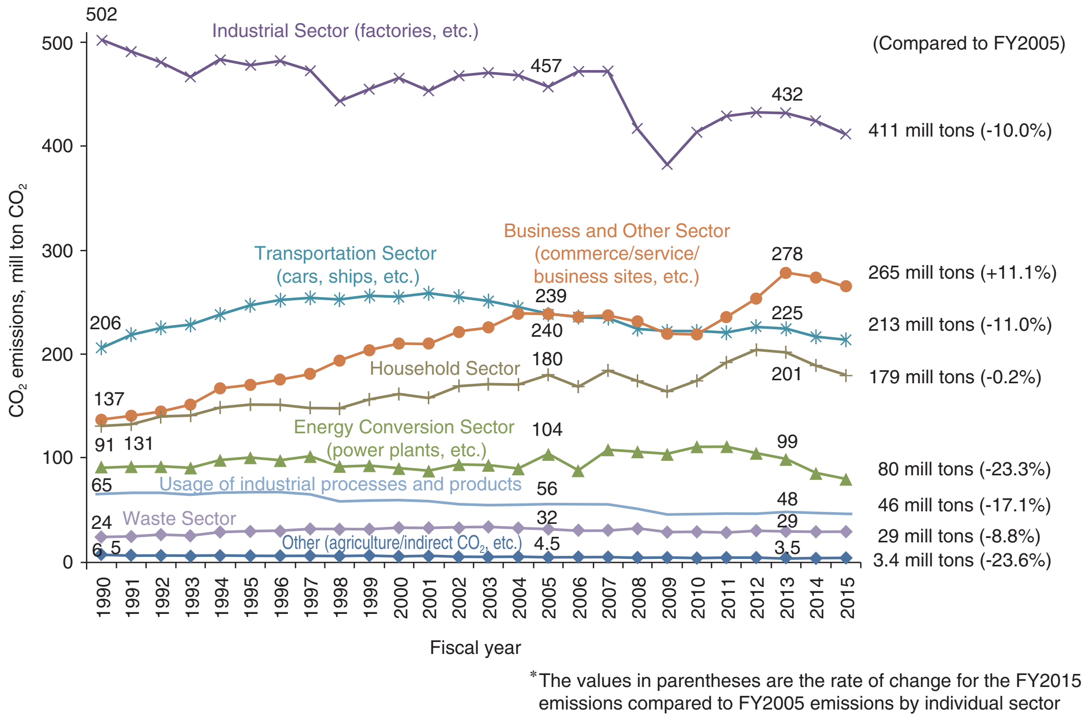

Fig. 1 Trends of CO_2 emissions by sector (after allocation of emissions from power and steam generation)

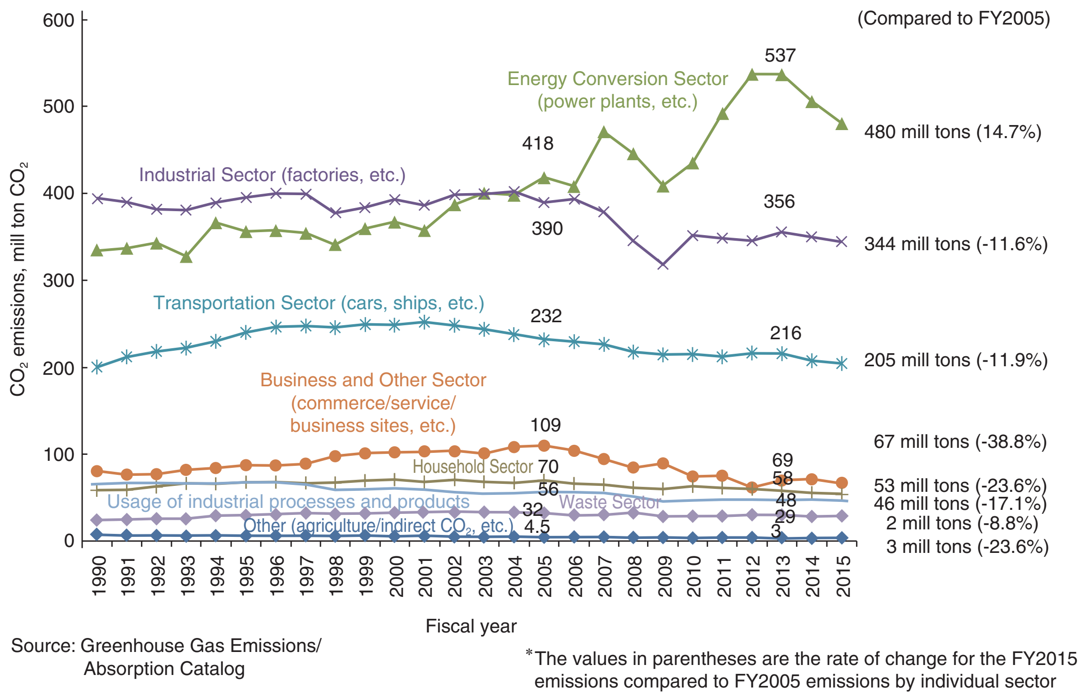

Fig. 2 Trends of CO_2 emissions by sector (before allocation of emissions from power and steam generation)

3. Current Status of Eco-machining

3. 1 MQL Machining Technique

Conventionally, the cutting process has involved supplying large volumes of cutting fluid to cutting points. The roles of cutting fluid in the cutting process are (1) lubrication, (2) cooling, and (3) cutting chip removal, and the reason why cutting fluid became a focal point of eco-machining is the large power consumption required for its usage. Depending on the type of machining, there are cases where over half of a factory's power consumption is by cutting fluid-related equipment[2)]. In the case of steel, the material's oxide film possesses lubricant properties, therefore oil-free dry machining is achievable with wide machining conditions. However, in the case of precision machining which affects heat generation, or the machining of aluminum alloy, etc., oil must be supplied to ensure sufficient lubrication performance. This led to the emergence of MQL (Minimal Quantity Lubrication), a form of eco-machining whereby an extremely small amount of oil (primarily naturally-derived ester) is supplied to the machining point in mist form.

MQL machining was first used by NASA in ultra-high-speed machining as a technique to supply oil to machining points. The technology was then advanced in Germany, a country with a high awareness of environmental issues. I stayed at RWTH Aachen University in 1995 and had the opportunity to be present at a research site for MQL. Here, the application limits of MQL had already been verified, with the conclusion being that, even with MQL and cool air combined, it was impossible to support the heavy cutting (ramping using an end mill) of aluminum alloy. I suggested to Prof. F. Klocke, director of the Laboratory for Machine Tools and Production Engineering (WZL), that perhaps it was necessary to use even just a small amount of water for heavy cutting, but he rejected this immediately, saying that they simply could not use water. The reason for this, I was told, was that German people are extremely fearful of leaking waste fluid into the Rhine, which flowed into other countries also.

With an awareness of the need to develop a new eco-machining technology, I returned to Japan and, considering that it would suffice as long as there were no waste fluid leakages, not to mention the fact that Japan had no rivers that flowed into other countries, I began research into MQL that used a small volume of water. Initially, I supplied water mist and MQL separately to the machining points but this did not work well at all, and in fact resulted in a larger cutting force than when MQL was used in isolation. I trialed various oil types used in MQL, and even developed an apparatus to supply water mist and oil mist from one nozzle, but met with failure upon failure. Meanwhile, in an experiment by a student engaging in graduation research, suddenly promising results were obtained. An investigation into how the good results came about revealed that the student had mistaken the water and oil supply pipes. Initially, the student had arranged it so that water mist was blown through the front and oil mist was blown through the back of a single nozzle. The order was probably made this way to ensure the water reached the machining point with certainty however, the student felt that it really didn't matter which was which. Nevertheless, water has a high surface tension and the particle size of water mist is larger than that of oil mist, therefore the water mist on its own reached the machining point first. The student had accidentally reversed this order, creating a situation whereby the water droplets first passed through the oil mist and became coated in oil, before reaching the machining point. Fortunately, the oil used on this occasion was rapeseed oil. Oil mist permeates the air in the surrounding vicinity, therefore in order not to negatively impact student health, and to prevent students from emitting an unusual odor after returning home from the lab, I had them use rapeseed oil, which is a familiar odor in the common household kitchen. I did not know that rapeseed oil and water had a low interfacial tension, therefore rapeseed oil spread swiftly across the surface of water. As a result, oil adhered to the water droplets that passed through the oil mist and spread swiftly, resulting in the configuration shown in **Fig. 3**.

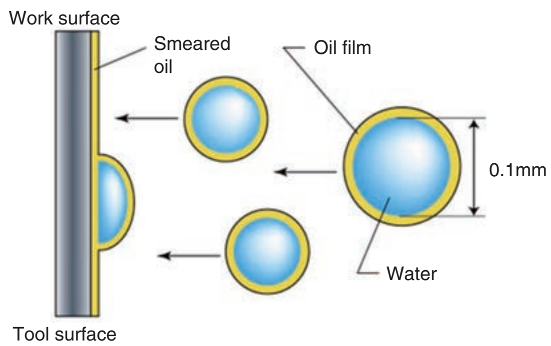

Fig. 3 Conceptual diagram of OoW (Oil on Water) cutting fluid

Figure 3 shows the OoW cutting fluid (OoW: Oil on Water) technique proposed by myself and the authors[3)], which can be considered a form of MQL due to the fact it only uses a minute amount of oil. The diameter of the water droplets are relatively larger, and the water-to-workpiece arrival rate is higher. The surface of these water droplets is coated in oil, and if the oil film thickness is equal, the larger the water droplet diameter, the smaller the volume fraction of oil relative to water will become. For the experiment, the standard water:oil ratio was made 100:1. For the oil mist, we used vegetable oil with the primary ingredient of tri fatty acid ester or synthetic ester with an added surfactant. Since long ago, vegetable and animal oils have been used as machining oils as these are biodegradable and offer good breakdown of bacteria. We experimented with a variety of oils, from olive oil to castor oil, but eventually settled on rapeseed oil as our standard in light of its machining performance for aluminum alloy, odor and price. Incidentally, soy sauce oil, which is treated as a fuel, has the highest performance on stainless steel, but was deemed inappropriate due to the students' dislike for the soy sauce smell and the fact that it would cause rust on the machine tool table, etc.

Figure 4 shows the results of performing heavy cutting using an end mill on aluminum alloy and testing the performance of OoW under various cutting fluid conditions[4]. The measuring result for cutting force of emulsion flood coolant (shown on bottom row of graph) of 200 N was made the standard, and it is only in the case of supplying refined rapeseed oil in mist form that the cutting force increases (shown on top row of graph). This is the "MQL application limit" confirmed at RWTH Aachen University, and it cannot be considered a good cutting state. Incidentally, in dry cutting, cutting chips weld with all tools and enter a state of friction stir welding (FSW). The second row of the graph shows that, if the water droplets alone are supplied, this also results in the cutting chips welding with the finished surface and cutting being unsuccessful. From the third row of the graph onwards, we used a combination of oil and water or OoW (water: 1 000 mL/h, oil: 10 mL/h) and changed the oil type. The first was normal mineral-based oil and, while cutting was achieved, the cutting force was large. The configuration shown in **Fig. 3** was not achieved because mineral-based oil does not spread across the surface of water. Secondly, we used edible frying oil, and this resulted in a lower cutting force than emulsion and a good finished surface. Thirdly, we used synthetic ester with added surfactant and this demonstrated an even lower cutting force. Fourthly, we used refined rapeseed oil and this had the second lowest cutting force, however there was no significant difference between the cutting forces for the last three oil types mentioned. My apologies to lubricant manufacturers, but this experiment showed us that the frying oil available off-the-shelf at supermarkets could sufficiently meet our requirements. However, if vegetable oil is used, just as in the household kitchen, oxidative degradation and polymerization leads to stickiness after extended periods of time, therefore regular cleaning is necessary.

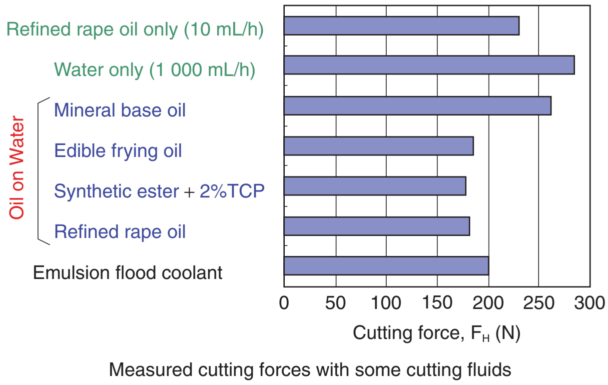

Fig. 4 Change in cutting force when using different supply methods and oil types

It is necessary to consider the water used in OoW also. We observed cases whereby OoW that worked well in the university laboratory in Nagoya city did not perform as well as expected when trialed in other regions. The water used in Nagoya city is soft water from the Kiso River, whereas the water sourced from underground used in other regions is hard, therefore performance was poor due to the imbalance of the water/oil interfacial tension. This problem was solved, however, by adding the right amount of surfactant to the oil.

OoW also uses air. From the perspective of power consumption, we want to minimize the supply of air compressed using a compressor. As such, we trialed blowing OoW on the machining points using water pressure and oil pressure alone. There was no great difference in the amount of air used by OoW when machining steel material, however there was a major difference in relation to aluminum alloy, for which the effects of oil are notable. In the case of steel, the machining temperature is high and the machining points are cooled by the water at boiling point. In contrast, the machining temperature of aluminum alloy is comparatively low and cooling is done with water at the heat of vaporization, therefore if the vicinity enters a saturated vapor state, it is no longer possible to vaporize and cooling performance falls. We realized that we needed a new way of supplying dry air. There was a need for different approaches to suit the material being machined.

3. 2 MQL Failed

MQL became known as an effective method for reducing the burden on the environment, and around 10 to 15 years ago, there was a strong movement primarily led by automakers and parts suppliers to introduce MQL to dedicated machining lines. I know factories that ordered custom-made tools for the introduction of MQL, flipped workpieces upside-down to improve the discharging of cutting chips created during drilling, and built cutting chip discharge systems to ultimately create factories capable of producing aluminum alloy parts in an eco-friendly environment. However, these were newly-constructed factories, and according to an employee of one particular equipment manufacturer who visits a lot of factories, there are many cases where factories left the existing production line as is and simply switched from cutting fluid to MQL, only to meet with failure. The reason why the switch to MQL was considered a failure are as follows:

1) Reduced discharging performance of cutting chips during drilling
2) No cooling performance with oil mist alone, and surface roughness worsened due to insufficient control of the built-up cutting edge
3) Due to the reduced cutting chip removal function, there were frequent cases of cutting chips becoming stuck in the jig seat, resulting in quality defects
4) When MQL is supplied from inside the spindle, oil mist undergoes centrifugation and the supply amount becomes unstable

I will discuss the issue of the cutting chips later, however in regards to the lack of cooling performance raised in point 2 above, this can be solved by adopting the OoW technique proposed by myself and the authors[3), or by blowing emulsion onto the target in mist form. Furthermore, in regards to point 4 above, a method has been developed whereby oil and air are supplied separately to the spindle then mixed in the vicinity of the tool (internal mixing method)[5).

As for the processing of cutting chips, this had been an issue of concern since the outset of OoW development. Cutting fluid such as emulsion does not only move cutting chips created at the machining point far from the machining point, it also adequately suppresses the scattering of cutting chips. In the case of MQL or dry machining, however, the cutting chips scatter in the air, and for MQL specifically, cutting chips adhere to the ceiling of the machine tool due to the stickiness of oil. Cutting chips may even penetrate the most unlikely of places in a machine tool and trigger various problems. In light of these concerns, we developed the system shown in **Fig. 5**. A custom-made end mill, drill and tap form a tool that sucks in the cutting chips from its tip[6) and cutting chips are sent to the collection/compression unit through the hollows in the tool, holder and spindle. The issue of point 4 above was solved by supplying OoW from the outside. Cutting fluid is sucked up together with cutting chips, therefore even when supplied from the outside, cutting fluid could be effectively supplied to the machining point. However, in order for this system to work, the cutting chips must be small enough to pass through the tool interior, therefore this method cannot be applied to heavy cutting.

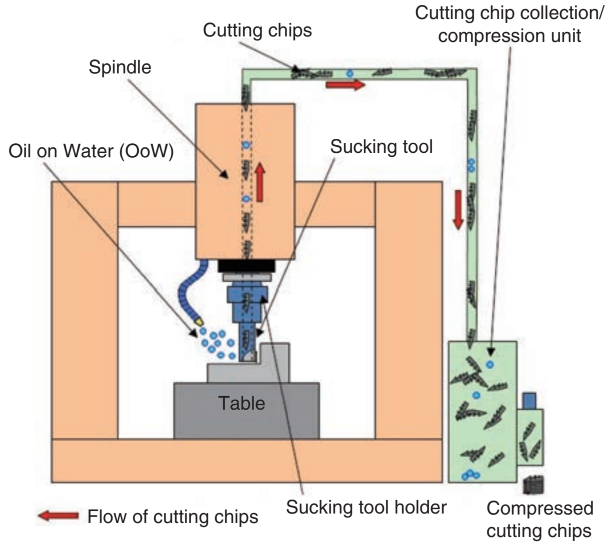

Fig. 5 Developed chip sucking machining system

3. 3 A New MQL Era

Even after the attempts to switch to MQL ended in failure, factories were still under pressure to reduce power consumption, therefore the technique of supplying emulsion cutting fluid in mist form (hereinafter referred to as “emulsion MQL”) is growing in popularity as a solution to the issue mentioned in point 2 above for existing equipment. For emulsion cutting fluid, surfactant is added to the oil and micelles form in the water. Oil disperses in water and the micelles are larger than the wavelength of visible light, therefore appear as white emulsion. If a certain oil concentration is reached or exceeded, an oil film also forms on the interface between water and air, therefore if emulsion is sprayed in mist form, it results in the same configuration as **Fig. 3**. However, micelles also exist within water droplets, therefore, in contrast to the water vs. oil volume of 100:1 for OoW, this ratio must be around 100:5 in the case of emulsion MQL. For regular machining, around 100 mL/h of emulsion MQL is supplied, and compared to OoW, both the amount of water and oil are reduced.

In either case, MQL lacks the ability to remove and discharge cutting chips therefore trials have been completed whereby washing agent is cascaded down the interior wall of a machine tool or air pulses are used to remove/discharge cutting chips while suppressing air consumption. Furthermore, if the sucking method shown in **Fig. 5** and the sucking tools developed by tool manufacturers (for example http://carbide.mmc.co.jp/magazine/article/cut_vol06) continue to be utilized, the issues mentioned in points 1 and 3 above could be solved. Also, in regards to passage through the spindle, if internal mixing is used to solve the issue mentioned in point 4, it is anticipated we would enter a new MQL era.

4. Conclusion

It is believed that the factories who introduced MQL to existing equipment "as is" between 10 and 15 years ago still consider this attempt to have been a failure. It is my hope that these factories refresh their view of MQL, which enables cutting with minimal oil. If the issue of cooling performance arises, emulsion MQL would be one potential solution, however I recommend OoW. In regards to supplying MQL through the spindle, interior mixing is an excellent method from the perspective of responsiveness. For all of these technologies, the related patents are due to expire in the near future, and I plan on recommencing development of a technology for sucking up cutting chips in a broad range of cutting. In closing, I wish to express my strong hope that Japan becomes one of the leading eco-machining countries in the world.

References

1) https://www.env.go.jp/earth/ondanka/cp/arikata/conf09/cp09_ref01.pdf, 44-45.
2) S. IKAWA, M. IWATSUBO, K. MIYAZAKI: Measures against Dry Machining for Environmental Response (in Japanese), Vol. 47, No. 5, (1999) 18.
3) T. NAKAMURA, T. MATSUBARA, F. ITOIGAWA, K. NIWA: Study on Minimal Oil Film on Water Fog Metalworking Fluid Emphasizing on Environment (in Japanese), Proc. of Japan Society for Precision Engineering Annual Meeting 1999 Spring, (1999) 550.
4) T. NAKAMURA, T. MATSUBARA, F. ITOIGAWA, K. KAWATA: Oil Film on Water Fog Metalworking Fluid, Proc. of 10th International Conference on Precision Engineering, (2001) 269.
5) T. MAKIYAMA: Near-dry Machining Technology for High Capability Machining Center, Society of Manufacturing Engineers IMTS 2000 Manufacturing Conference, (2000), CD-ROM, Session #210.
6) T. NAKAMURA: Necessity for Newly Developed Tools and These Far-reaching Effects (in Japanese), Vol. 54, No. 3, (2010) 10.