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BIOMACHINING-A REVIEW

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Abstract—Micro-manufacturing is one of the fastest growing technologies and non-traditional machining processes have been found to be beneficial for micro manufacturing using low density of energy for metal removal. In biomachining the metabolic function of the bacterium is utilized, no physical or chemical energy needs to be focused at the machining point, thereby avoiding the possibility of
generating a damaged layer or a heat-affected zone in the machined surface. In biomachining, microorganisms are used to create the desired part(s) of the metals to the required dimensions. In this study an attempt has been made to understand the basics of "Biomachining" along with the factors effecting the output performance characteristics.

Keywords—biomachining; Acidithiobacillus ferrooxidans; metal removal rate;

I. INTRODUCTION

Non-traditional micro-machining processes are becoming more popular now a day in industries for micro fabrication. Micro machining of mmaterialsCla can be performed by three different methods i.e physical, chemical, and biological methods [1]. Fig 1 shows the classification of material processing from the view point of energy used.

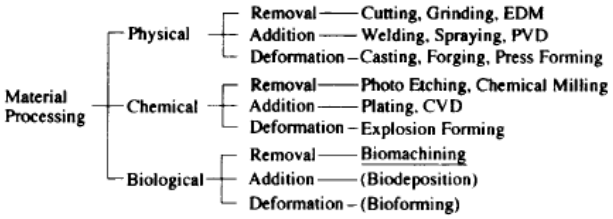

Fig. 1 Classification of material processing from the view point of energy used and volume change

In micro-machining, high-density of energy is used to remove a very small amount of material which wastes much energy. Even though the physical and chemical methods of machining are very fast, they have some impacts on the dynamics of processes in biotic and abiotic systems outside the boundaries of the work space. It has been observed that microorganisms, attack structures and induce corrosion. If this microbe-induced corrosion process can be controlled and guided in a specific direction, an environmentally benign, energy-efficient, and cost-effective approach can be developed for material processing applications[2]. Since last few decades, chemolithotrophs bacteria have been used by many researchers in biomachining for micro fabrication. Uno et al.[1] reported the first fundamental study on the possibility of biomachining. Ting et al.[2] compared metal removal by biomachining and chemical machining. Fig 2 shows the various microorganisms used for biomachining.

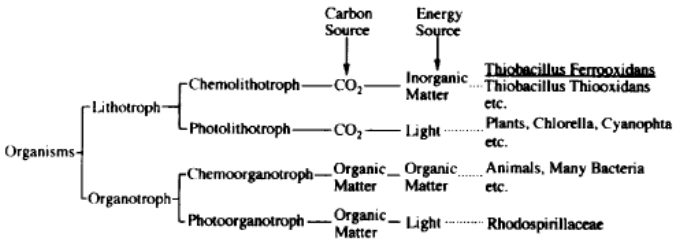

Fig. 2 Classification of organisms

Johnson et al.[3] reported the surface characteristics of biomachining polycrystalline copper for specific initial bacterial concentrations. They described an increase in roughness of the work-piece, which was proportional to the machining time. Hocheng et al. [4] showed the metal removal rate (MRR) by Acidithiobacillus thiooxidans bacteria without pre-secreted metabolite. Istiyanto et al.[5,6] reported the profile and surface characteristics of biomachining uni-crystal copper. They reported a U-shaped profile for a rectangular groove with width and depth that increase proportionally to the machining time. Recently, Jadhav et al.[7] reported the possibility of biomachining with only ferric ions by removing bacteria from a culture solution and Eskandarian et al.[8] reported the enzymatic biomachining using glucose oxidase. All these studies reported the capabilities of biomachining for micro fabrication.

II. MECHANISM OF BIOMACHINING

The ability of microorganism to leach and mobilize metals from solid materials possibly involves three principles: (i) redox reactions, (ii) the formation of organic or inorganic acids, and (iii) the excretion of complexing agents. The reactions involved in biomachining can be characterized as a biological redox reaction and can be described as:

$$2Fe^{+2} + \tfrac{1}{2}O_2 + 2H^+ \rightarrow 2Fe^{+3} + H_2O \qquad (1)$$

$$Fe^0 + 2Fe^{+3} \rightarrow Fe^{+2} + 2Fe^{+2} \qquad (2)$$

The first part of these reactions is the continuous conversion of Fe^{2+} to Fe^{3+} by bacterial metabolism, which involves the transfer of electrons from ferrous iron. The second process is completed by the uptake of electrons by oxygen and combining with H^+ ions, resulting in water. The goal of these two processes is to produce useable energy for the bacteria.

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The energy-creating process forms a closed system for Fe^{2+} ions as they are continuously converted to Fe^{3+}, exuded from the cell, reduced to Fe^{2+} by their reaction with copper or iron, and then reabsorbed into the periplasmic space for re-oxidation. On the other hand, H^+ ions are consumed continuously and water is produced. Hence it can be concluded that, if the metabolic activity of bacteria can be improved by tuning process conditions such as temperature, shaking rate, and H^+ ions(pH), the most crucial shortcoming of biomachining can be eliminated.

III. EXPERIMENTAL METHODS FOR BIOMACHINING

The experimental procedure of biomachining consists of four major steps, (1) bacteria culturing (2) workpiece preparation (3) bacterial density measurement, and (4) metal removal rate calculation. For culturing A. Ferrooxidans bacteria (ATCC No. 21834) in liquid media, Silverman's media (modified 9K) with 14.75% w/v $FeSO_4$ solution in DI water is used except the experiments for observing the effect of $FeSO_4$ variation.[11] The composition of basal salts is shown in Table 1.

Table 1. Components of 9 K Medium

· $(NH_4)_2SO_4$	30g
· K_2HPO_4	5g
· $MgSO_4$	5g
· KCl	1g
· $Ca(NO_3)_2$	0.1g
· Deionized Water	10L
· Adjustment of pH to 2.5 with H_2SO_4	
· $FeSO_4$	3 vol %

The culture of bacteria is carried out by sterilizing an appropriate volume of 9K medium in an autoclave. Then this culture fluid is inoculated in 9K medium and shaken in both X and Y direction.

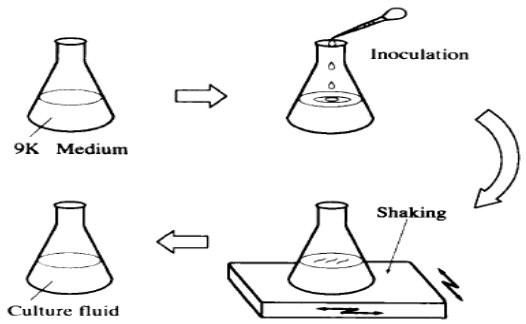


Fig. 3 Schematic diagram of culture of bacteria

For bacterial density measurement, solid media was prepared by solidifying 9K media using agarose solution. The formula used to calculate bacterial density is given below.

$$\text{Cell density (Cells/mL)} = \frac{\text{number of bacterial colonies}}{\text{dilution factor} \times \text{vol. of diluted broth inculated}} \quad (3)$$

The bacterial density remains almost constant during 48 hours to 60 Hours. The formulae used to measure Material Removal Rate (MRR) and Specific Material Removal Rate(SMRR) are given below.

$$MRR = \frac{\text{mass before biomachining} - \text{mass after biomachining}}{\text{biomachining time}} \quad (4)$$

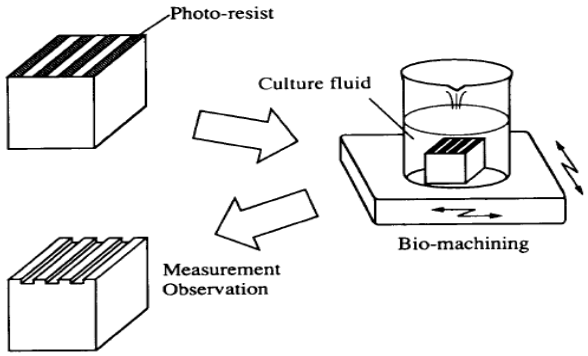
$$SMRR = \frac{\text{mass before biomachining} - \text{mass after biomachining}}{\text{biomachining time} \times \text{exposed area} \times \text{bacterial density}}$$

For metal removal the mask pattern used to form the groove is previously prepared on the workpiece by photolithography process.The machine groove counter on the workpiece is measured by surface profilometer. The mean depth of the groove can be considered as the removal amount.

Fig. 4 Schematic diagram metal removal experiment

III. RESEARCH WORK IN BIOMACHINING

Uno et al. [1] carried out pioneering work in the biomachining of metals. They showed the potential of *At. ferrooxidans* in material processing. They employed a very basic experimental



setup for the biomachining of metals[Fig. 1]. For the biomachining experiment, pure copper and iron metals were employed. The mask pattern used to form the grooves was previously prepared on the workpiece by the photolithography process. The culture of *At. ferrooxidans* was grown in a 9 K medium at 28°C and 160 rpm. This culture solution was taken in an open beaker, and the pure copper and iron metals were added into the beaker separately to start the biomachining process. The researchers found that the groove depth for copper and iron increased linearly with machining time by using the culture medium with bacteria. On the other hand, the amount of metal removal by chemical etching was minimal. Also, there was some data on the effects of changing some of the parameters such as temperature and shaking conditions on biomachining of copper. In their work, they found that application of electric field during the biomachining process was effective. In electric-field-assisted biomachining, the metal removal rate at the anodic workpiece became much higher than that in normal biomachining, whereas the removal amount at the cathodic workpiece was minimal. Zhang and Li performed an experiment very similar to the one by Uno et al. [1]. The sample was prepared once again using the existing photolithographic techniques. The prepared sample was then incubated with the bacteria for a period. Finally, the sample was removed periodically and measured both with a

profilometer and a scanning electron microscope [9]. Furthermore, they proposed a model of ion cycle in the biomachining processes. They also discussed measures for maintaining the stable equilibrium of the ion cycle. Biomachining of copper by *At. ferrooxidans* is a complex thermodynamic process because Fe3+ is strongly hydrolyzed, resulting in the generation of H+. In the machining pure copper, the rate of generation of H+ owing to the hydrolysis of Fe3+ was lower than the rate of consumption of H+ owing to the oxidation of Fe2+, resulting in a gradual increase in the pH. If H+ is not added at all times to adjust the pH to about 2, an increase in hydrolysis is observed, which ultimately decreases the growth of *At. Ferrooxidans* [10]. The necessary conditions for maintaining the stable equilibrium of the biomachining system are the supply of H+ and the removal of Cu2+. To overcome this problem, H2S gas was bubbled into the solution. This gas supplied H+ ions and generated CuS. The CuS was precipitated, and the Cu ions were removed from the solution. The results of Zhang and Li [10] also indicate that the rate of biomachining depends directly on bacterial concentration.

The results of Yasuyuki et al. [11] suggested the feasibility of material removal at microscale levels in the biomachining of controlled microstructures in low carbon steels using *At. ferrooxidans*. *At. ferrooxidans* converted Fe2+ into Fe3+. The ferrite microstructures of steel were subjected to preferential corrosion, caused by the Fe3+ ions produced by *At. ferrooxidans*. The ferrite that existed in the submicrometer-scale gaps in the steel microstructure was dissolved selectively by Fe3+ ions. Kurosaki et al. [11] also used the corrosive Action of aerobes and anaerobes for the biomachining of metals. Recently, a study was carried out to characterize the surface roughness and to quantify the material removal rate in biomachining [3]. Both parameters play important roles in obtaining precision products through the micromachining process. The quality of the surface produced is a very important aspect of the performance of the manufacturing process. Every manufacturing process, however, has limitations regarding this characteristic. It is therefore important to explore the surface finish characteristics of the biomachining process. Johnson et al. [3] have included experiments on the surface roughness produced by biomachining. However, they did not explain the explicit relations and the trendlines of relations between surface roughness and machining time. Istiyanto et al. [5] investigated the surface roughness and the material removal rate characteristics in the biomachining of copper for various machining times. In this study, the surface appearance of workpieces changed after biomachining for both 800- and 220-grit-polished workpieces. The biomachining process caused the arithmetic average of surface roughness (Ra) to increase at various rates for 6, 12, and 18 h of machining times. The researchers also found that the metal removal rate during biomachining was inversely proportional to the machining time but not simply linear. In another study, several shims with a thickness of 0.1 mm, a diameter of only 2 mm, a thickness of 0.07 mm, and diameters of 15 mm and 16 mm were fabricated using this biomachining method [12]. In this study, the change in surface roughness was also investigated. Surface roughness increased rapidly with time, from less than 0.2 mm to close to 2 mm. The surfaces of each slice of every material were damaged. They also found that in the first 2 h, roughness increased linearly with time. The surface quality deteriorated rapidly, and at the end of the 2 h, the surface roughness of the three kinds of materials reached the worst, and then became stable. Beyond the 2 h, it no longer increased significantly, but fluctuated within certain limits and then reached the stable stage eventually [12].

IV. CONCLUSIONS

An innovative metal removal process termed biomachining has been investigated using the Acidithiobacillus genus bacteria (At. ferrooxidans and At. thiooxidans). Several metals were successfully biomachined using these bacteria. Biomachining does not pose any problems of damaged layer or a potential damage to metallurgical properties of the workpiece like other unconventional processes wherein chemical or thermoelectric energy is concentrated at the machining point. More importantly, seen in the context of a future where industrial technologies must be more environmentally friendly and utilize “mild” process conditions, this metal processing technique appears promising. Research work is required to improve the rate of biomachining and the surface finish, and obtaining a better understanding of the mechanisms involved in biomachining.

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