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Influence of Micro Droplets of PVD-coated Tool on Tribological Conditions in Cold Forming

Kazuhito Asai[1], Kazuhiko Kitamura[2], Sukunthakan Ngernbamrung[3],Takuma Ise[4] and Chikara Matsuda[4]
[1] Department of Mechanical Systems, Faculty of Engineering, Toyama Prefectural University, 5180 Kurokawa, Imizu, Toyama 939-0398 Japan
[2] Electrical and Mechanical Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466-8555 Japan
[3] Academic Assembly Faculty Engineering, University of Toyama, 3190 Gofuku, Toyama, 930-8555 Japan
[4] R&D, TL Division, YUKEN INDUSTRY CO., LTD., 123-Doinouchi, Takatana-cho, Anjo, Aichi 446-0053 Japan
kazuhito-asai@pu-toyama.ac.jp, kitamura.kazuhiko@nitech.ac.jp, sukunthn@eng.u-toyama.ac.jp, isetakma@yuken-ind.co.jp, matudtkr@yuken-ind.co.jp

Abstract

Hard coating possibly improves die-life for the cold forming. Moreover, PVD-coated tools retain precise geometries due to lower coating temperature. However, many micro droplets scatter on the PVD-coated tool by arc ion plating. In this paper, the influence of micro droplets on tribological conditions was investigated when TiN-coated tools with the micro droplets were used for a tapered-plug penetration test. The forming load and the surface quality were estimated in the test. These were damaged by adhesion under the condition of a thin lubricant film between the tool and workpiece, while the micro droplets cannot affect both tools and workpiece under another well lubrication condition of a thick lubricant film.

1 Introduction

Hard coated tools have been widely used for cold forming to improve die life, precise geometries and surface qualities of products. The hard tools made of die steel or cemented carbide are covered with hard coating mainly for metal forming using physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal diffusion processing (TD). PVD coated tools for precision cold forming make great progress, which is possible to maintain the designed geometries of the tool with small thermal-distort due to the low temperature during the coating process. Recently, in the PVD coating, the bonding performance between the tool and the coating has improved to use practically for severe cold forming such as precision cold forging, sheet metal forming, blanking, and ironing, although coating by CVD coating and TD process is the higher bonding performance than PVD coating. Thus, the PVD coating has been applied to many forming tools of punches, dies, and containers for precision cold forming to improve the service life of the tools and supply the products with high quality.

A practical PVD by arc ion plating contributes to the wide usage of the effective tools for sheet metal forming and cold forging. In the PVD process arc plasm vapor a targeted cathode metal. The vapored metallic ions and react gas are drawn to the anode tools. The vapor and the radical gas received electrons from the anode to produce the designated coating on the tool surface. The election flows with micro droplets directly reach the tool surface during the PVD process.

The coating layer partially includes the micro droplets, which does not affect when the sizes are smaller than the lubricant film under a well-lubricated condition for mild forming. Recently the industrial needs light weight using high strength material and high forming reduction. Thus, the metal forming has required demanding hard conditions of high pressure, long sliding, elevating temperature, and large surface expansion. These conditions cause a poor-lubricated condition as the lubricant film is too thin or nearly dry to increase some risks of pick-up, galling, and wear increase. Osakada et al. (Osakada, K. et al., *Annals of the CIRP*, 2000) reported that DLC coating resulted in low-friction in dry forming of aluminium and that the oxide layer on steel resulted in high friction in cold forging under Al, Cu and low C-steel by ring test upsetting with CVD coated with TiC, TiC+TiCN+TiN, and PVD coated with TiN, TiAlN and DLC. Groche et al. (Groche P. et al., WTC, 2001) reported better wear resistance of CVD coated TiC + TiN than PVD coated CrN and TiN with a number of tool coatings in a cold extrusion test of steel wire. Dubar et al. (Dubar M. et al., *Wear*, 2005) reported a wear analysis of a c cold forging tooling for heading of a bolt in 34Cr4 steel comparing PVD or CVD coating with TiN of AISI M2 tool steel. Aizawa et al. (Mitsuo, A. et al., *Surface and Coatings Technology*, 2000) (Akhadejdamrong, T. et al., *Wear*, 2003) (Mitsuo, A. et al., *Materials Transactions*, 2003) (Aizawa, T. et al., *Surface and Coatings Technology*, 2004) reported that development of a TiN coating with low-friction and wear-resistant properties in metal forming. A report by Miki (Miki, Y. et al., *Report of Nara Prefectural Institute of Industrial Technology*, 2000) showed that these micro droplets caused wear during a ball-on-disk test. Koseki et al. (Koseki, S. et al., *Precision Engineering* 44, 2016) reported that using TiN-coated cutting tool with the surface defects could reduce damage of the coated cutting tools, increasing tool life. Kanazawa et al. (Kanazawa, R. et al., *Transactions of the Society of Automotive Engineers of Japan*, 2025) reported that damage to PVD-coated tool in press working was caused by adhesion of the work material in concave areas formed after droplets generated during film deposition were removed by polishing. In this study, a tribological influence of the micro droplets is estimated experimentally using a tapered-plug penetration test. The penetrating load is measured during the test. The surface of the tool and workpiece are observed.

2 Experimental method and conditions

Figure 1 illustrations the outline of the tapered-plug penetration test. The tapered plug is made of high-speed steel with a maximum diameter of 16.67 mm, and a taper angle of 5º. The workpiece is made of 0.10% carbon steel. It has an outer diameter of 29.9 mm, an inner diameter of 13.3 mm, and a height of 50.0 mm. A punch pushes a tapered plug into the hollow workpiece at an average speed of 180 mm/s. Beef fat is applied to the hole of the container in common with any testing conditions.

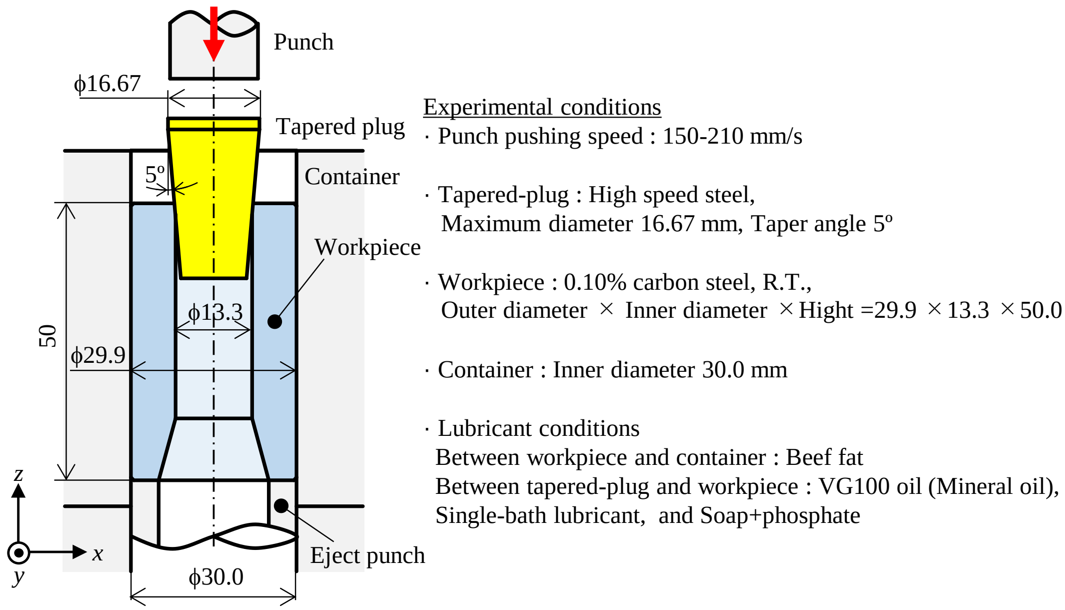


Figure 1: Outline of tapered-plug penetration test

Figure 2 shows the SEM images and surface profiles of the tools before the tapered-plug penetration test. The roughness of the tapered plug was 0.4 μm Rz before TiN coating by PVD process. Micro droplets are observed on the TiN coating after the process. The droplets increase the roughness of the surface after the coating process. The maximum height of the micro droplet is estimated at approximately 5 μm. Some TiN-coated tools were polished with #600 emery paper after coating. The micro droplets on the surface were removed after polishing. Some sharp-edged holes appear on the surface of the TiN coating.

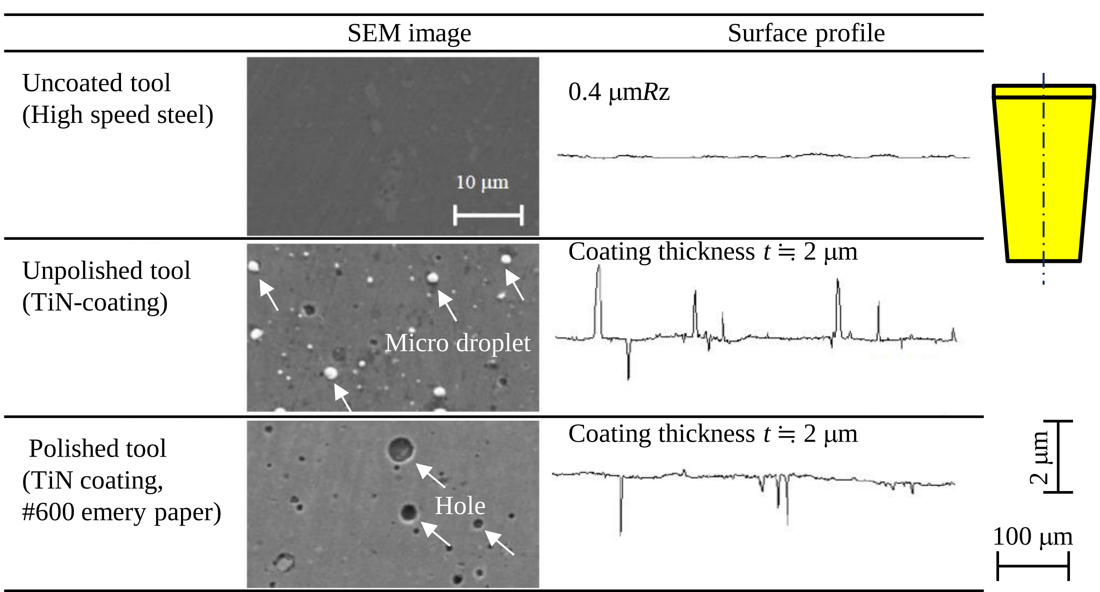


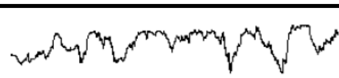
Figure 2: SEM images and surface profiles of the tools before the tapered-plug penetration test

Table 1 shows the lubricant conditions for the test. VG100 oil is a mineral oil with a viscosity of 100 mm^2/s. VG100 is often used for base oil to produce lubricant oil for cold forming. Single-bath lubricant is a solid lubricant for cold forging and can be applied to the workpiece in a single lubricating process. This lubricant is expected to reduce industrial emissions but keep the lubricated performance for cold forming. Soap-phosphate is a solid lubricant formed by conventionally applying sodium stearate onto zinc phosphate coating which is widely used for hard cold forming. However, it includes a harmful chemical lubricating process to environment. Thus, the cold forming industry attempts to switch from the conventional Soap-phosphate to the Single-bath lubricant of phosphate-free type.

Lubricant	Liquid / Solid	Amount of applying	Viscosity (40ºC)
VG100 oil (Mineral oil)	Liquid	Fill	100 mm^2/s
Single-bath lubricant	Solid	16 - 20 g/m^2	-
Soap-phosphate	Solid	36 - 43 g/m^2	-

Table 1: Lubricant conditions

Figure 3 shows the surface profile of the workpieces after tests when the polished tool after coating is used. The profiles are measured parallel to the tapered-plug penetrating direction. When Soap-phosphate is applied, the surface of the inner workpiece was roughened freely without flatted areas by direct contact with the tool. When Single-bath lubricant is applied, both freely roughened and almost flat areas are observed. When VG100 oil is applied, the thin lubricant film formed rather larger flat areas than Single-bath lubricant. These observations suggest that the Soap-phosphate is thicker than Single-bath lubricant and VG100 oil; VG100 oil is the thinnest among the testing lubricant. According to the fundamental lubrication theory in metal forming, a free roughening surface can develop with larger plastic deformation if a thick lubricant film like the Soap-phosphate is held between a workpiece and a tool under a well-lubricated condition. This roughening behavior must be restricted in a thinner lubricant film like the Single-bath lubricant. Consequently, roughening surface is locally flatted but other areas remain roughening. If the lubricant film like VG100 oil is thinner than the Soap-phosphate and Single-bath lubricant, the flat areas increase by compressing the projections of the roughening surface. Thus, the thin lubricant film helps to manufacture a smoother product, but it sometimes brings pick-up of products or tool wear upon. Therefore, the thickness of Single-bath lubricant is estimated at the same level as height of the micro droplet. Soap-phosphate is fully thick for micro droplets. However, VG100 oil is too thin to lubricate well when the tool with the micro droplets is used.

Lubricant	Surface profile	Maximum surface roughness [μmRz]	Equivalent lubricant film thickness Rz /2 [μm]
VG100 oil (Mineral oil)		2	1
Single-bath lubricant		5	2.5
Soap-phosphate		5	2.5 <

10 μm

100 μm

Polished coating, Measuring direction : penetration direction

Figure 3: Surface profile, maximum surface roughness Rz, and equivalent lubricant film thickness

3 Results of experiment

Figure 4 shows typical tapered plug penetration load curves. VG100 oil was applied to the inner side of the workpiece. The penetration load rapidly increases at the early stroke using the unpolished tool after TiN-coating. The maximum penetration load reaches about 185 kN. Many micro droplets were observed on this unpolished TiN-coated tool before the test. In contrast, the maximum penetration load significantly falls 85 kN to be about 100 kN when used the polished tool after TiN-coating. There are no protruded droplets but many small holes with sharp edges. Polishing the PVD-coated tool by arc ion plating is helpful to reduce the load.

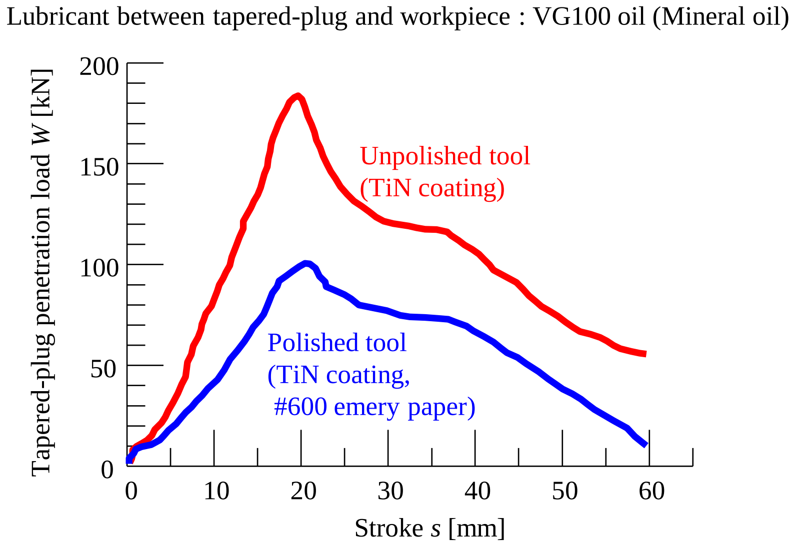


Figure 4: Tapered-plug penetration load curves using VG100 oil

Figure 5 shows the inner surface of the workpiece after the test at a stroke of 20 mm from the entrance. Several deep scratches are observed here using the unpolished tool after TiN-coating. When used the polished tool after TiN-coating, the light scratches are observed on the inner side of the workpiece after the test. When used the unpolished tool after coating or the tool as coated, several deep scratches are clearly observed here. Scratching the surface needs more additional load than forming a smooth surface without streaks. Therefore, the tapered-plug penetration load also rapidly increases using unpolished tool after coating as shown in Figure 4.

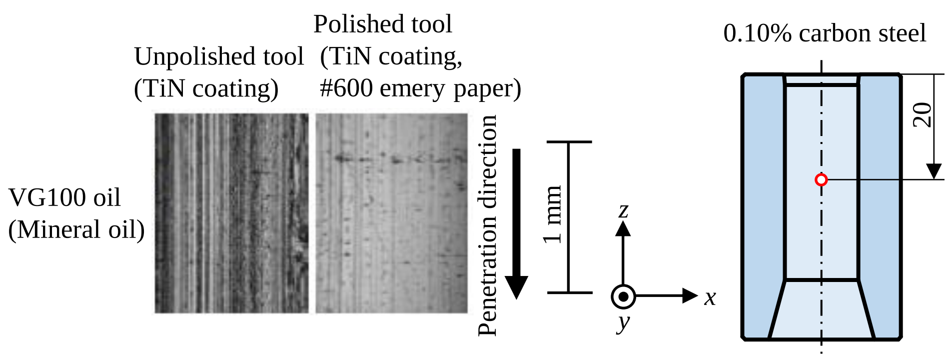


Figure 5: Observation of inner surface of the workpiece after the test

Figure 6 shows the compression of maximum tapered-plug penetration load W_{max} under different lubrication conditions. Using the polished tool after TiN-coating contributes to help to reduce the forming load under any lubrication conditions; however, some different effects of the polish after coating appear for each lubrication conditions. Disregarding the after-polishing, the lubrication of Soap-phosphate shows lower load than other two lubrication. When Single-bath lubricant and VG100 oil are used, the after-polishing is significantly effective in reducing load. The amount of Soap-phosphate is applied much greater than that of Single-bath lubricant. A thick lubricant film exists between the coating and the workpiece during the test. According to a rough estimation of lubricant film thickness by Figure 3, Soap-phosphate is sufficiently thicker than other Single-bath Lubricant and VG100 oil. Moreover, Soap-phosphate and Single-bath lubricant are initially solid lubricants but VG100 oil is not solid. Generally, solid lubricant keeps the thickness at early contact and forming, and liquid type of oil easily releases out of the interface between the tool and the workpiece. Probably, the thicker lubricant film direct contact between the micro droplets and the workpiece can be prevented if the lubricant film does not break out. In the actual forming processes, it is necessary to remove micro droplets on the hard coating before forming to prevent an increase in forming load and keep good quality of the products.

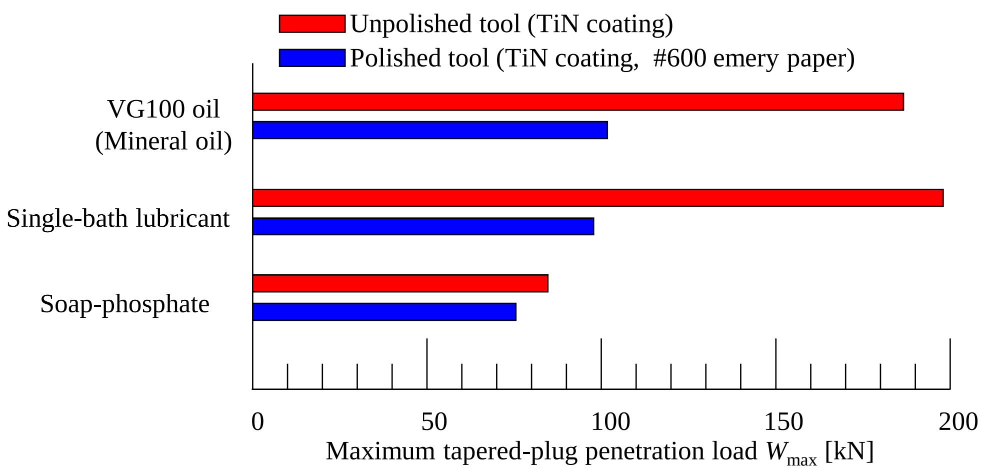


Figure 6: Comparison of maximum tapered-plug penetration load W_{max} under various lubrication conditions

Figure 7 shows the scanning electron microscope (SEM) images and the results of energy dispersive X-ray spectroscopy (EDS) analysis on the TiN-coated tool when the unpolished tool after coating was used under Single-bath lubricant. Fig. 7 (a) shows around a typical micro droplet as well as the results of EDS analyses of Fe, Ti, and N. According to the high intensity of Fe, the adhesive matter or galling matter is transferred from the workpiece to the right side of the micro droplet. In the other larger region apart from the galling region with Ti and N are clearly counted. Thus, this region means the TiN-coated or droplet itself. The galling matter seems to be growing parallelly in the direction to penetrate the TiN-coated tool. Fig. 7 (b) shows the SEM images and EDS results around a typical hole that appeared after micro droplet removal. The high intensity of Fe is counted on the left side of the hole. The galling matter can be transferred from the workpiece because it seems to be cut off by the sharp edge of the hole.

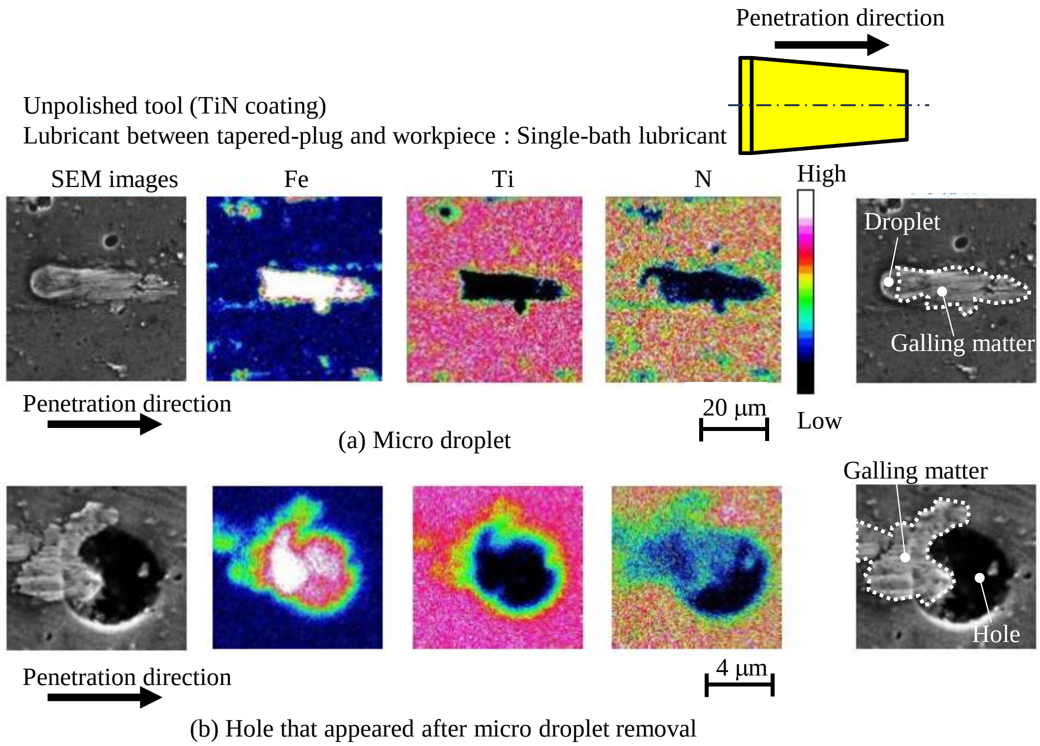


Figure 7: SEM images and results of the EDS analysis on the surface TiN-coating after test

Figure 8 schematically illustrates two typical images of a micro droplet and the thin and thick lubricant film. In Fig. 8 (a) the top of the micro droplet can directly contact the workpiece because the lubricant film is thin to be often broken. Consequently, the micro droplet scratches the surface of the workpiece and increases the load by additional friction under the poor lubrication condition. Fig. 8 (b) reveals a well-lubricated state that the tool with micro droplets is out of contact with the workpiece surface by thick lubricant film. Such a thick lubricant film can protect the workpiece against hard contact and the lower load.

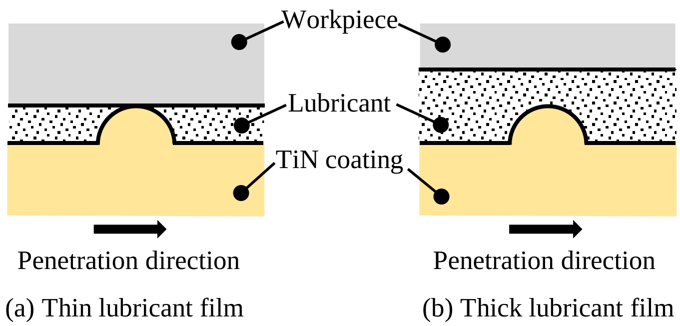


Figure 8: Schematically of two typical images of a micro droplet and the thin and thick lubricant film

4 Conclusions

The tribological influence of the micro droplets was estimated experimentally by a tapered-plug penetration test. Many micro droplets were observed on the TiN-coated tools by PVD with arc ion plating before the test. The polished or unpolished tools after the coatings were used for the test under the different lubricants-film thickness. The following results were obtained:

1. Maximum penetration load using the polished tool after TiN-coating was lower than that using the unpolished tool after TiN-coating when Single-bath lubricant and VG100 oil were used. Polishing the PVD-coated tool by arc ion plating is helpful to reduce forming load.

2. Several deep scratches are observed on the inner side of the workpiece after test using the unpolished tool after TiN-coating when the workpiece was lubricated with VG100 oil. It was necessary to remove micro droplets from the PVD-coated tool to keep good quality of the products, particularly under a condition of a thin lubricant film such as VG100 oil and Single-bath lubricant.

3. Galling matter of the workpiece were observed in micro droplets or holes that appeared formed after micro droplets removal using SEM. Particularly, micro droplets scratched the surface of the workpiece, and increase the load by additional friction under the thin lubricant film, whereas a thick lubricant film could protect the workpiece against hard contact and the lower load.

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