# Effects of TiO2 nanoparticle lubricant on micro deep drawing performance

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**Research Article**

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Dear Editors,

We would like to submit an original research manuscript entitled "**Effects of $TiO_2$ nanoparticle lubricant on micro deep drawing performance**" for consideration by The International Journal of Advanced Manufacturing Technology. This manuscript builds on our prior study to determine the evolution of the forming at micro-scale and has not been published anywhere else nor is currently under consideration for publication elsewhere.

1. The main contribution to this field:
    - The effects of the $TiO_2$ water-based nanoparticles lubricant on micro-cups made of SUS301.
    - The forming velocity can affect the asperities of the workpiece surface and microcup's profile, and the relationship between the drawing velocity and lubrication efficiency can be determined.
    - To evaluate the quality of formed-cup, wrinkling value, height derivation, and surface roughness were considered by meaning of various characteristic parameters, which show the improvement of the product's quality.
2. The novelty:
    - The $TiO_2$ nanoparticle water-based lubricant has been approved to be efficient in reducing the friction to the mechanical process in the conventional scale, however, this lubricant has not been widely investigated in the micro deep drawing.
    - Most of previous researches on the MDD are focused on the effects of processing parameters such as, anisotropy, friction, die arc radius, punch radius, blank holder force and material grain size. It is novelty that, studying the forming velocity under the dry and lubricant conditions can benefit to find the mechanics of the MDD, and then improve the microproduct's quality.

3. The industrial application

    - MDD provides a great application for producing cylinder parts, ladder parts, spherical parts, rectangular parts and so on, besides, more complex parts can be formed if combined MDD with other manufacturing method. In this paper, the enhanced micro-cups have many industrial applications in aircraft structural parts, communication industry and medical devices.

This manuscript is original and not under consideration for publication elsewhere. We have no conflicts of interest to disclose.

Please address all correspondence regarding this manuscript at dp794@uowmail.edu.au or jiang@uow.edu.au. Thank you for your consideration.

Sincerely,
Di Pan

# Effects of $TiO_2$ nanoparticle lubricant on micro deep drawing performance

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## Abstract

Micro deep drawing is a process to manufacture the thin walled, hollow, box or cup like products at micro scale. Lubricant can affect the products' quality in micro deep drawing at micro scale due to the decrease of coefficient of friction between the material and tools, it is crucial to enhance the forming efficiency. In this study, 40 μm thickness stainless steel 301 (SUS301) was annealed at 980 °C for 2 min under protection of argon gas ambient, and this stainless steel was selected as the specimen material. The micro deep drawing was conducted on a micro press machine under dry and 4% $TiO_2$ nanoparticle lubrication conditions with different forming velocities. The experimental results showed that the micro cup's profile is affected by changing the forming velocity under the dry and nanoparticle lubrication conditions. Under the dry condition, the surface became rough with the increase of the forming velocity, and then the micro forming efficiency under application of nanoparticle lubricant increases with a rise of drawing velocity.

**Keywords:** Micro deep drawing · Forming velocity · Size effects · Nanoparticle lubricant · SUS301

# 1. Introduction

There is a global trend to minimise the manufactory products' pollution, volume and cost among medical, automotive, and telecommunication sectors, then this requirement encourages to develop the diversity and accuracy of micro-manufacturing products. Besides, the micro forming is one micro manufacturing technology, which is used to produce the high accuracy and comprehensive metal components in cost-effective bulk production [1-3]. The micro forming can be separated into two categories according to different bases. Namely are micro-electromechanical system (MEMS)-based lithographer technology, which is relatively well-established for semiconductors, microelectronics and MEMS field; the other one is mechanically based on macro manufacturing processes [4, 5]. To manufacture hollow, thin walled, box or cup like products at micro-scale, the micro deep drawing (MDD) is a fundamental process of the micro forming, and more complex parts can be formed if combined the MDD with other manufacturing methods [1, 6]. Since the MDD becomes crucial in producing micro-parts, a well-founded knowledge is essential to explain the frictional behaviour and used to manufacture high-quality products [7, 8]. To improve the quality and formability of the products in MDD, several researches have been conducted. The quality and profile accuracy of the formed parts can be influenced by the friction on the contact surface, the material grain size, and tool's dimensions [9, 10]. In the MDD, the coefficient of friction (COF) is affected by the drawing velocity, however the high forming velocity indicates high strain rate, which can also affect the products' quality [11]. Besides, the diamond-like carbon (DLC) film coated tool can be used to reduce the friction significantly and improve the limiting drawing ratio [12, 13]. Although, micro products were well produced by using the DLC film coated tool in the MDD, the expense of this method was much more compared with the normal lubrication condition, which means using DLC film coating is not suitable for mass production [14]. The nanoparticle lubricant is utilised to improve the microproduct's surface quality, because the nanoparticle lubricant film can act as an adhesive film to uniform the stress. Furthermore, the wrinkling, height derivation and earing phenomenon can be diminished via the lubricant film on the tools. The contact length can determine the development of stationary lubrication status and the COF, besides the forming velocity may affect the forming efficiency of nanoparticle lubricant applied [15, 16].

This article presents an experimental study on forming austenite SUS301 micro cups with different forming velocities under the dry and lubrication conditions. The micro cup's vertical view, side view and the surface roughness are observed by the 3-D laser microscope. The mechanical property and profile of the micro cups are characterised, then the MDD efficiency are expected to be improved by altering the forming velocity and utilising the nanoparticle lubricant. In addition, the different forming velocities are investigated to enhance the lubricant's efficiency, and then explore how the lubricant working in the MDD.

# 2. Experimental

## 2.1 Experimental material

The SUS301 is widely used in industrial engineering due to its high corrosion resistance, toughness and well plastic forming characteristics. In this study, the SUS301 sheet with a thickness of 40±2 μm was chosen as test material. The composition of the SUS301 is listed in Table 1. Annealing was performed at 980 °C for 2 min in KTL tube furnace under the protection of gas ambient. Using argon gas is efficient to prevent the material from oxidation during the annealing, then the sample was cooled down in the furnace under argon gas ambient until it reached the room temperature. After that, the alcohol and eraser were used to remove the contaminants and oxidation layer on the sheet surface before the drawing experiments.

**Table 1.** Chemical compositions of SUS301

| C | Si | Cr | Mn | Ni | N | P | S | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.15 | 0.75 | 16.00-18.00 | 2.00 | 6.00-8.00 | 0.10 | 0.045 | 0.030 | Balance |

## 2.2 Micro deep drawing

The MDD was carried out on a Desk-top servo press machine DT-3AW as shown in Fig. 1 (a), which can generate up to 25 KN forming force. Besides, the control box and die set are illustrated in Fig. 1 (b), and then the control box can control the blanking and forming velocities during the MDD. The die set contains the lower and upper dies, and there are the force sensor, upper blank holder and punch in the upper die; the lower die contains the spring, die cavity and lower blank holder. The working principle of the MDD set up is shown in Fig. 2 and Table. 2 shows the experimental geometrical parameters. During the MDD, the punch force was recorded by the force sensor and analysed in the computer, besides, it is one stroke forming process and contains two forming stages. The first stage is blanking and the second is forming. In the blanking stage, the blank holder in the lower die acts as the blanking punch, which moves upward and cut a round blank from the stable sample. In the forming stage, the blank's rim is fixed by the upper and lower blank holders, and then the punch pushes the round blank into the die cavity to manufacture the micro-cup.

**Table 2.** Parameter of press machine DT-3AW and process

| Punch diameter (mm) | Die diameter (mm) | Radius of punch fillet (mm) | Radius of die fillet (mm) | Initial blank diameter (mm) |
|---|---|---|---|---|
| 0.8 | 0.975 | 0.3 | 0.3 | 1.6 |

## 2.3 Lubricant

Adding the nanoparticles (NPs) into water based lubricant has been proved to be an efficient method to enhance the anti-wear properties and friction-reduction ability of the lubricant. The characteristics of NPs in lubricant such as size, shape and concentration can determine the reduction of friction and wear. Generally, smaller NPs can affect the friction, bring smaller COF and reduce the wear, besides spherical NPs are more likely to roll on the surface compared to non-spherical ones. The higher NPs concentration lubricant are more readily agglomerated, which can weaken the lubricant ability to decrease the friction and wear, and thus an optimal concentration exists. The water based 4% $TiO_2$ nanoparticle lubricant is selected in this study due to its low cost, nontoxicity, superb dispersibility and stability. The base of this lubricant is glycerol, which is a colourless, odourless and viscous liquid. To prepare this lubricant, firstly mixed the $TiO_2$ nanoparticles (approx. 20 nm diameter) into the deionised water by mechanical stirring, and then drop in the polyethyleneimine (PEI), which performed as the surfactant of $TiO_2$. At last, added the aqueous glycerol and stirred the lubricant by ultrasonication to break down remaining agglomeration.

In this study, MDD tests with different blanking and forming velocities were performed to study the effect of blanking and forming velocities on the quality of drawn cups. The blanking and forming velocities were executed in 0.1, 0.2 and 0.3 mm/s respectively, and then the products' quality and surface morphologies in these groups were observed by the 3-D laser microscope. Firstly, the blank surface and edge quality were observed, and the optimal blanking velocity was settled. After that, the different forming velocities were investigated in the MDD under the dry and lubrication conditions with this blanking velocity. With the observation on the micro products of the MDD under different conditions, the forming velocity's impact on the micro product's quality and efficiency of nanoparticle lubricant could be determined.

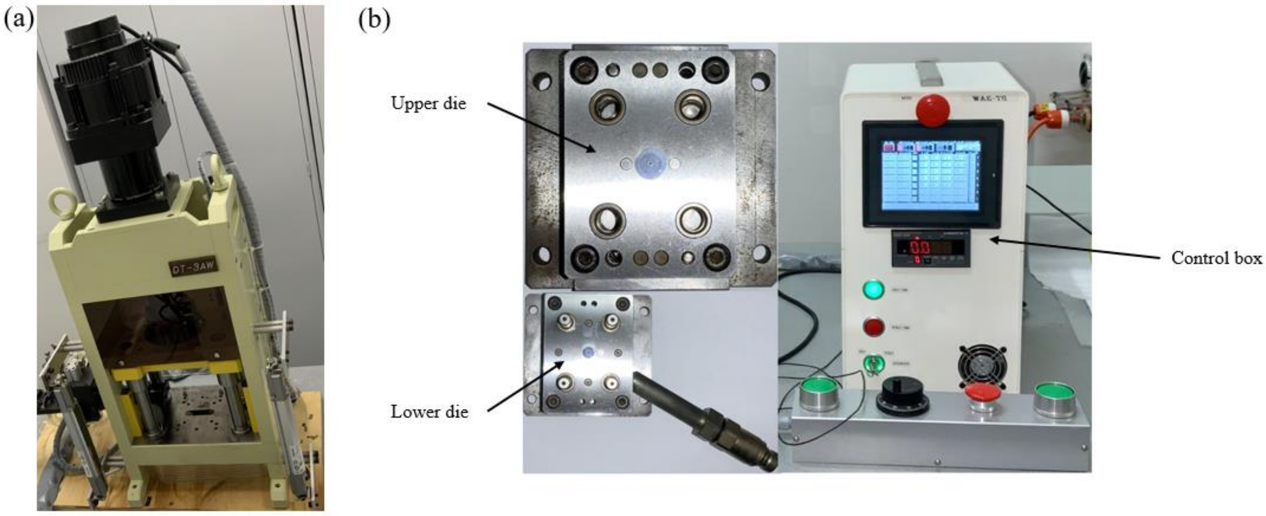


**Fig. 1.** MDD apparatus. (a) Press machine DT-3AW; (b) MDD die set and control box

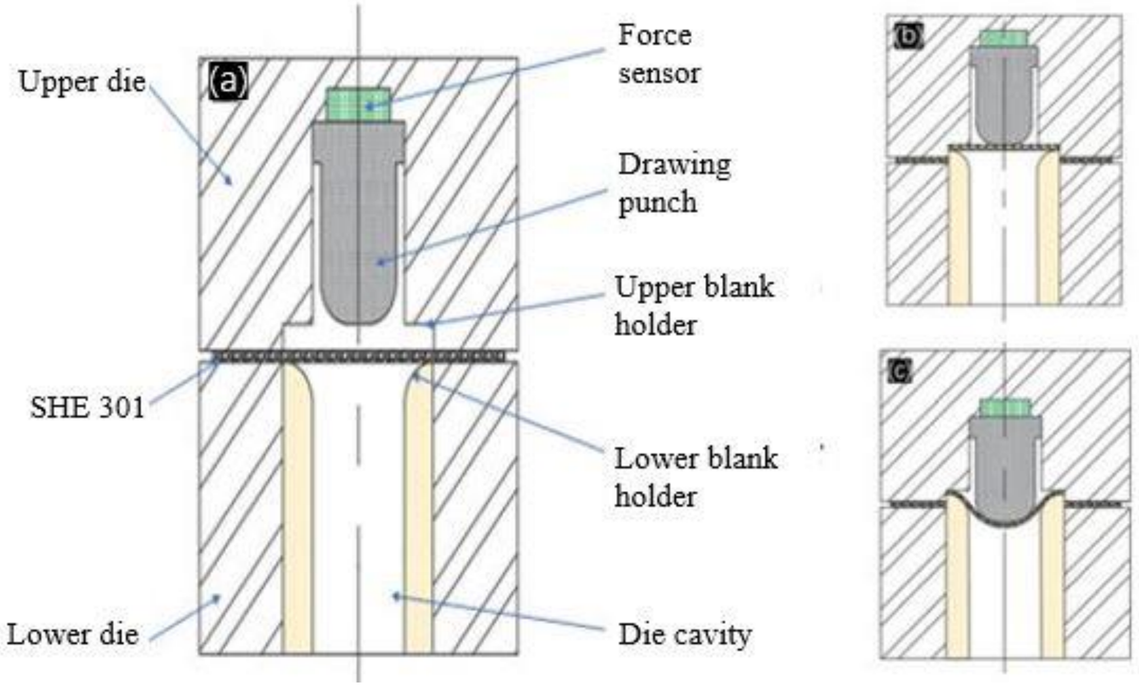


**Fig. 2.** Schematic of MDD processes: (a). Initial stage of MDD, (b) Blanking stage of MDD, (c) Forming stage of MDD

## 3. Results and discussion

The influences made by different blanking and forming velocities on the drawing behaviour were more pronounced in microforming, because the so-called ‘size effect’ would cause the inhomogeneity of material flow behaviour and the surface condition effect on the sample. Then the effects of the blanking and forming velocities are significant on micro product’s quality and lubricant’s efficiency.

### 3.1 Effect of blanking velocity on blank asperity

The different blanking velocities can affect the specimen profile due to the scatter of the material plastic deformability at micro-scale. Besides, different blanking velocities cause the scatter of grain plastic deformation due to the different breakage rate on the blank edge [17, 18]. Consequently, it provides another method to understand the effect of blanking velocities on the deformation behaviour of the samples and the quality of drawn microparts. As shown in Fig. 3, the profile of the blank edge was captured by the laser scan microscope. From this figure, it can be seen that the blank with 0.1 mm/s blanking velocity has the most bending area among the 0.1, 0.2 and 0.3 mm/s blanking velocities. The asperities of the blanks processed with different blanking velocities reveal significant distinctions and the curve area of the blanks’ edge under different blanking velocities are totally different. This phenomenon is due to the sheet tends to bend into the upper die during the blanking process, and more area can be squeezed into the upper die with the lower blanking velocity

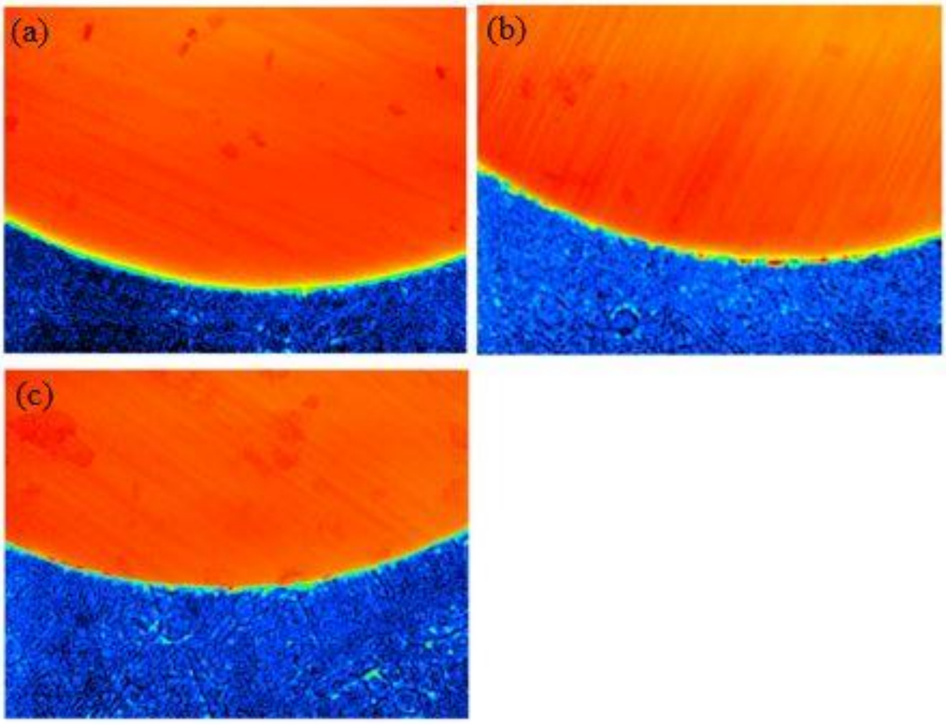


**Fig. 3.** The blank edge of specimens under different blanking velocity: (a) 0.1 mm/s blanking velocity, (b) 0.2 mm/s blanking velocity, and (c) 0.3 mm/s blanking velocity

After blanking, the blank's edge jag phenomenon is not same under the different blanking velocities. On the one hand, the sample interior grains' deformation behaviour is not homogenous, which can cause the unevenness of the blank edge. On another hand, the different blanking velocities cause different breakage rates around the blank edge, and the differences of microstructural change in shear zone under different blanking velocities are significant. The jag on the blank edge is produced, which can affect the micro products' quality in the next stage [19-22]. As a single grain becomes crucial to the deformation of specimen at microscale, the breakage rate of grains in the blank's edge are various in different blanking velocities, which can cause the various deformation on the blank edge [23]. The jag phenomenon is significant with the low strain rate, when the strain rate decreases, the blanking force reduces and the blanking time increases, and then the inhomogeneity of deformation could be aggravated. During the blanking process, some grains boundaries could not be broken down with an insufficient blanking force at a low blanking velocity, and the deformation transfers to the weaker grain boundary of the material, which is not on the deformation route, then produces the jag area. Meanwhile, the blanking time increases at the low blanking velocity, which can improve the possibility to deform these weak grain boundary. After the blanking process, the round blank sample is produced and then will be manufactured in the MDD. During the MDD, wrinkling is easily formed with the insufficient and inconsistent blank holder force (BHF) on the blank's edge [24-26]. Besides, the blank edge's jag and bending area are crucial elements to affect the BHF. In the MDD process, the blank holder pressure is constant and generated in the contact area between the blank and blank holder. When the contact area contains less jag and bending area, the blanking edge is flat and consistent. Therefore, the sufficient and continuous BHF can be generated on the blank edge, which is blanked with high blanking velocity, then benefit the deep drawing in the next stage.

## 3.2 Effect of velocity on deep drawing

To evaluate the effects of different forming velocities on the MDD, the behaviour of the sample in the MDD process was investigated. Since the 0.3 mm/s blanking velocity was determined to reduce the bending area and improve the blanks' edge quality in the blanking stage, the different forming velocities with 0.3mm/s blanking velocity are studied in the MDD under the dry and lubrication conditions. Fig.4 shows the comparison of the drawing force under these conditions. Compared with different forming velocities, there is a similar trend of the drawing force to the displacement under the dry and lubrication conditions. As the punch moves downwards, the blank deformation resistance increases. Effective punch force ($P_e$) was obtained by collecting the data of punch force as

$$P_e = F_b + F_s + \left(F_{fbh} + F_{fdie}\right) \tag{1}$$

where $F_b$ is the bending force at the die shoulder, $F_s$ is the drawing force at the flange, $F_{fbh}$ is the friction between the blank and the blank holder, and $F_{fdie}$ is the friction between the blank and the die.

Initially, the dominated punch force is the resistance of bending and other force is small, meanwhile, the deep drawing force increases slowly. Then the blank edge slips out from the die sets and the drawing force decreases slowly, after that the large deformation of the blank proceeds high-flow stress, and the friction force increases simultaneously with more contact area [7, 12, 27]. Therefore, the punch force increases rapidly in this period, then the punch force reaches the peak point and remained in a short period. Since the blank is slipped easily into the lower die under the lubrication conditions, the thickness was thicker with less bending force and time. The more force was needed to deform the thicker blank in the forming stage, and therefore the forming force under the lubrication condition is more than that under the dry condition with the same forming velocity. As the deformation continuing, the force decreases until the end of the drawing process. Moreover, due to the stored strain energy in the drawn cup, the punch force was not zero at the end of the forming process, and then the drawn cup released the strain energy gradually at the end of the drawing process [28].

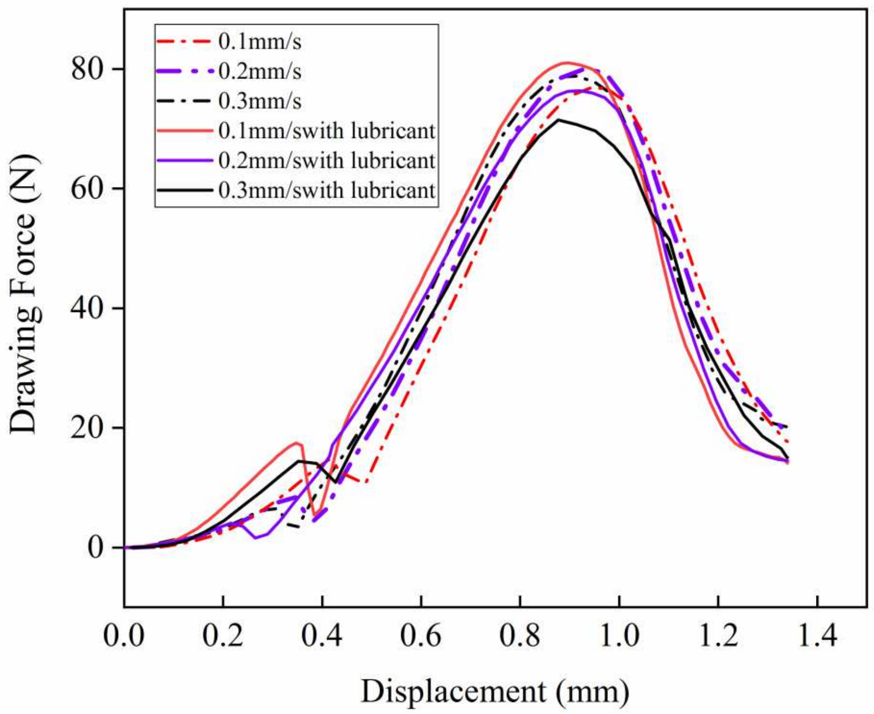


**Fig. 4.** Drawing force-displacement curve with different forming velocities

The effects of forming velocities on the MDD were investigated to improve the products' quality. In strip drawing, the COF is affected by the drawing velocity and this phenomenon can also be observed in the MDD. The COF in micro forming is higher than that in the macro forming due to the tribological size effect, and the COF decreases when the punch velocity increases during the MDD process [11]. However, the forming with the higher velocity means the higher strain rate during the forming process, which needs more force to accelerate the deformed area to the higher forming velocity [29, 30]. At the beginning of the forming process, the punch force is larger with the higher forming velocity because of the higher strain rate, then the contact area between the sample and die becomes larger as the MDD processing. Consequently, the difference of punch force between the different forming velocities becomes small due to the decrease of friction force with the higher forming velocity. Meanwhile, the more strain energy can be restored at end of the process, and the formed cups need springback to release the stored strain energy gradually. This phenomenon can be described via the last stroke drawing force, because the punch is squeezed by the micro products at the end of the drawing process, and then the last stroke force is generated. Furthermore, when the more strain energy needs to be released at the end of MDD, more force compresses the punch and is transferred to the force sensor [29, 31, 32]. The last stroke drawing force in all of conditions is plotted in Fig. 5. In the dry condition, the last drawing stroke force is reduced from 21.2 to 18.86 N and reaches at 16.72 N, when the forming velocity decreases from 0.3 to 0.2 mm/s and achieves at 0.1 mm/s. Therefore, micro cups with a lower forming velocity store less strain energy compared with the higher forming velocity, and the remarkable reduction of the last stroke drawing force can indicate the significant effect of reducing the forming velocity. Forming the micro cup with slower punch velocity can reduce the stored strain energy of the micro cups, and then improve the products' quality in the MDD.

There is a similar trend of force to displacement under the dry and lubrication conditions, since the lubricant is dipped into the lower die and attached on the die wall, which has not changed the MDD mechanism. The nanoparticle lubricant film can act as an adhesive film to uniform the stress and the nanoparticles can absorb the strain energy during the forming process. Besides, under the lubrication condition, the last force is generally lower than that under the dry condition in the same forming velocity. Under the lubrication condition, the last stroke is 16.04 N with 0.3 mm/s forming velocity and decreases to 15.51 N when the forming velocity is 0.2 mm/s, then reaches 14.1 N with 0.1 mm/s forming velocity. The difference of the last drawing force stroke between the dry and lubrication conditions becomes large with the increase of forming velocity. Therefore, the lubrication efficiency enhances with the higher forming velocity, and the stored strain energy can be decreased when using the 4% $TiO_2$ nanoparticle lubricant.

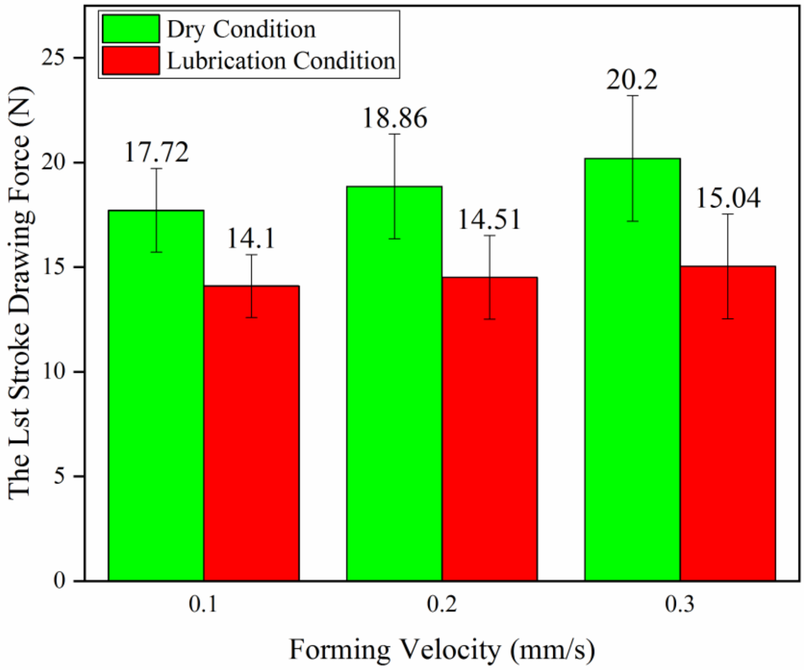


**Fig. 5.** The last stroke drawing force comparison

### 3.3 Micro conical-cylindrical cups

Images of conical-cylindrical cups with 0.3 mm/s blanking velocity and different forming velocities under the dry and lubrication conditions are illustrated in Fig. 6. It shows that micro cups can be formed by the MDD apparatus with different forming velocities under the dry and lubrication conditions. For all forming velocities, wrinkling occurred at the cup edge. As can be seen, under the dry or lubrication conditions, the cups drawn in 0.3 mm/s forming velocities had noticeable winkles, whereas the cups drawn under the lower forming velocities had smoother cup mouths. Therefore, wrinkling can be prevented by altering the forming velocities. Like the surface roughness parameter, two indexes were defined to analyse the wrinkles quantitatively (Eqs. (2) and (3)). To observe the wrinkling nodes on the drawn cup mouth, the position coordinates and a reference circle were exported, and the wrinkling angle related to the reference circle point can be measured with the image as shown in Fig. 7. Then the average summation of the wrinkle peak and valley heights was used to calculate the wrinkle value. These equations are:

$$R_{ti} = \frac{R_{pi} + R_{vi}}{2} \tag{2}$$

$$R_w = \sum_{i=1}^{N} R_{ti} * \partial_i \tag{3}$$

where $R_{ti}$ is the wrinkle value at point $i$, $R_{pi}$ is the wrinkle peak height at wrinkle point $i$, $R_{vi}$ is a wrinkle valley depth at wrinkle point $i$, $R_w$ is the wrinkle value of the drawn cup and $\partial_i$ is the wrinkle angle at wrinkle point $i$.

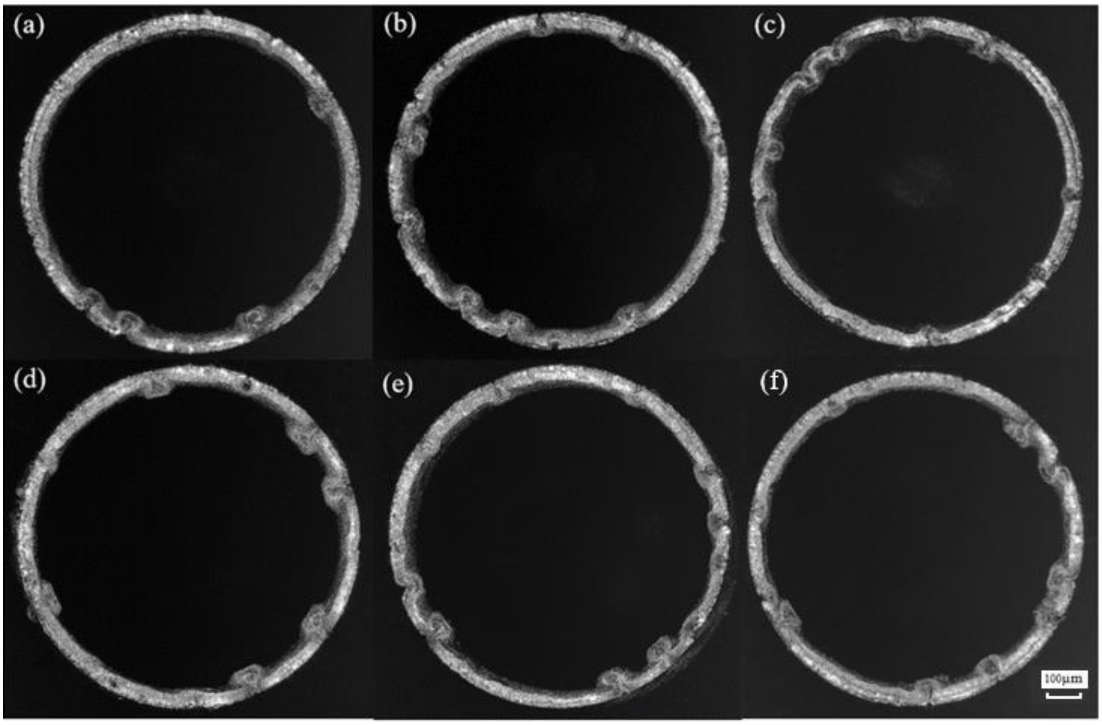


**Fig. 6.** Drawn cups' mouth view in different forming velocities: (a) 0.1 mm/s in dry condition, (b) 0.2 mm/s in dry condition, (c) 0.3 mm/s in dry condition, (d) 0.1 mm/s in lubrication condition, (e) 0.2 mm/s in lubrication condition, and (f) 0.3 mm/s in lubrication condition

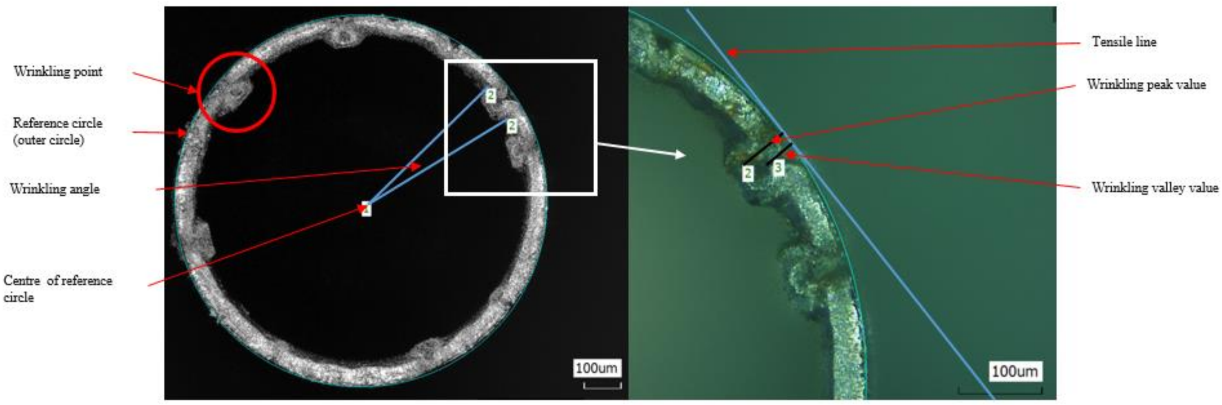


**Fig. 7.** Wrinkling measurement of drawn cups

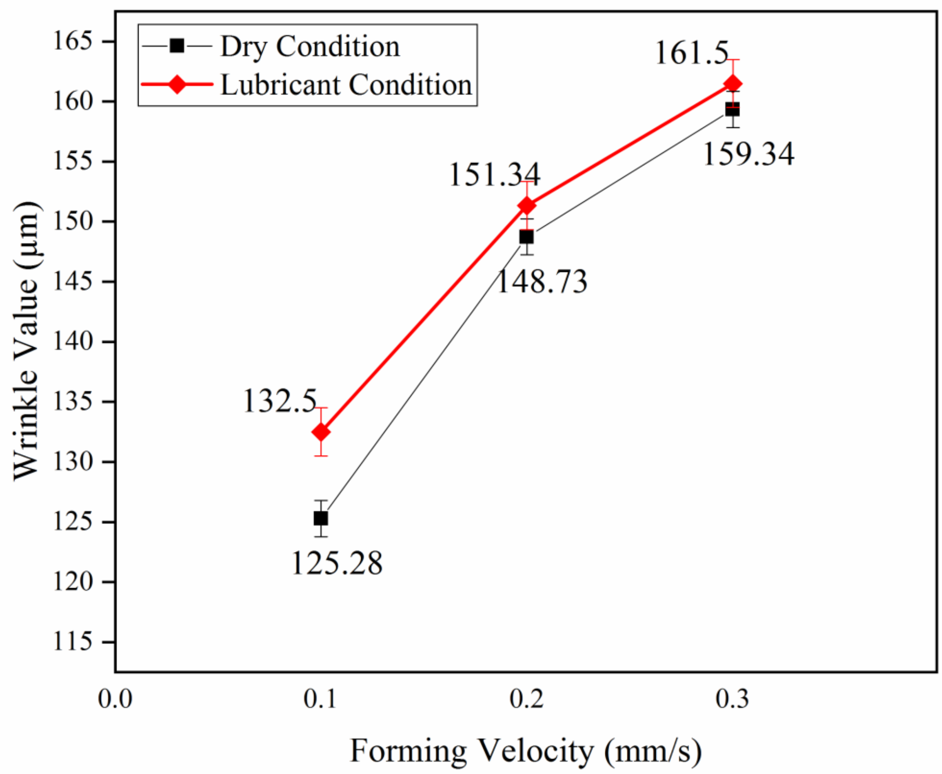


**Fig. 8.** The wrinkling value of drawn cups

The defined wrinkling values of drawn cups are shown in Fig. 8. Under the same blanking velocity (0.3 mm/s), the 0.1 mm/s forming velocity has the smallest wrinkle value and gradually increased with a rise of forming velocity. These wrinkles values are increased sharply when the forming velocity is higher than 0.1 mm/s. In the initial forming stage, the blank edge is fixed by the die sets, then the punch moves downward and compelled the blank into the drawing cavity, meanwhile, the fixed area decreased as the forming process went. Furthermore, the fixed area minimised quickly with the high forming velocity, and the blank holder provides the constant pressure on the fixed area during the forming process. Therefore, the BHF decreased significantly with minimising fixed area, and then the flange can wrinkle because of the inadequate BHF. Furthermore, the blank flange's uneven deformation can also cause the wrinkling. Nevertheless, the blank flange is easily deformed unevenly with high strain rate during the forming process, because the inhomogeneous deformation occurs easily with large flow stress [7, 12, 33, 34]. The forming velocities can directly affect the stress in the radial, thickness, and circumferential directions, besides, this stress state's change can influence the wrinkling on the cup mouth and the whole drawing process significantly. The difference of stress between the radial and thickness directions becomes large when increases the forming velocity due to the higher strain-rate. Therefore, the wrinkling decreases significantly with the low forming velocity. Besides, the relationship between the wrinkling values and the forming velocity can be effected by the material inhomogeneity, material hardening, and blank deformation path, then this relationship becomes relatively complicated. Under the lubrication condition, the wrinkling of the micro cups has the same trend with the dry condition, the wrinkling phenomenon becomes detectable when increase the forming velocity. During the MDD, the 4% $TiO_2$ nanoparticle lubricant forms the film between the sample and lower die, which refers to reduce the friction by separating the tool and sample from direct contact. Besides, this film contains the nanoparticles, which are likely to roll on the contact surface then reduce the friction. Considering the reduction of the friction between the blank and lower blank holder, the blank slipped out easily. Therefore, the BHF could be insufficient with the small fixed area and the wrinkling is easily formed. On another hand, the BHF can be compensated by the lubricant, which is trapped in the close pocket. Because the lubricant in the closed pockets can withstand the contact pressure effectively based on the open-close lubrication theory [15, 35-37]. Compared with the dry condition, the wrinkling is more evident under the lubrication condition with 0.1 mm/s forming velocities. However, there is not significant difference of wrinkling phenomenon between dry and lubrication conditions, when the forming velocity increases to 0.2 or 0.3 mm/s. Since the fixed area of the blank decreases fast under 0.2 and 0.3 mm/s forming velocities, then the lubricant effects slightly on the micro cup’s mouth with small contact area and short function time. Above all, the wrinkling is more easily generated under 0.1 mm/s forming velocity, when using the 4% $TiO_2$ nanoparticle lubricant compared with dry condition, and there is not significant difference between the lubrication and dry conditions when the forming velocity is 0.2 or 0.3 mm/s.

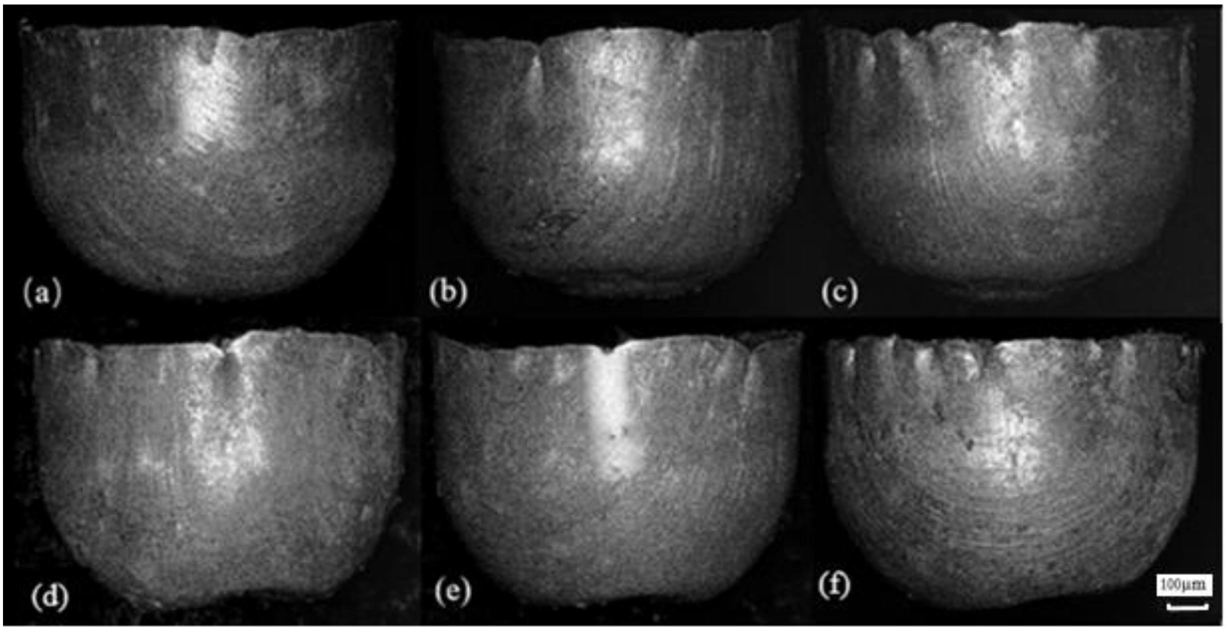


**Fig. 9.** Drawn cups' side-view in different forming velocities: (a) 0.1 mm/s in dry condition, (b) 0.2 mm/s in dry condition, (c) 0.3 mm/s in dry condition, (d) 0.1 mm/s in lubrication condition, (e) 0.2 mm/s in lubrication condition, and (f) 0.3 mm/s in lubrication condition

Fig. 9 shows the cups' side views, which are fabricated by MDD with 0.3 mm/s blanking and different forming velocities under the dry and lubrication conditions. In contrast, with different forming velocities, these micro cups' heights are not even under dry or lubrication conditions. However, the deviation degree is different under these conditions, and the cups' height deviations were caused by unevenly distributed stress on the cup wall and inhomogeneous material formability [38-40]. From this research, these deviations can be minimised via altering the forming velocity and using lubrication. To analyse the cups' height deviation, nine points are selected at the cup mouth to measure the heights, then the average height can be calculated and used for height deviation by the equations. These equations are:

$$H_{avg} = \frac{\sum_{t=1}^{9} Ht}{9} \tag{4}$$

$$H_{dev} = \frac{\sum_{1}^{9}\left(H_t - H_{avg}\right)}{9} \tag{5}$$

where $H_t$ is the cup height at point t, $H_{avg}$ is the average height of nine points and $H_{dev}$ is the cup's height deviation.

Fig. 10 shows the cups' height deviation values, which are related to the forming velocity and lubrication condition. The smallest height deviation value is 8.81 μm, when the forming velocity is 0.1 mm/s under dry condition; and the micro cups' height is the most even under this condition. Besides the height deviations increases with the higher forming velocities, this value increases to 11.78 μm when the forming velocity is 0.2 mm/s and reaches 13.35 μm with 0.3 mm/s forming velocity. Nevertheless, compared with the dry condition, the height derivation decreases when using the lubricant under 0.2 or 0.3 mm/s forming velocities, and this value increases under 0.1 mm/s forming velocity. Besides, the difference of the height derivation between dry and lubrication conditions is more significant with a rise of forming velocity. The inhomogeneous material deformability can cause the misalignment, and the specimen profile can be affected by the scatter of material plastic deformation during the forming process. The drawn cup would not have the uniform cup height and would exist noticeable earing, which can be observed in Fig. 10. Regardless of the lubrication condition, in the case of the same sample size, the irregular geometry of the drawn cups is significant with the high forming velocity, because the high strain-rate leads to occur the inhomogeneous deformation more easily. Furthermore, the 4% $TiO_2$ nanoparticle lubricant can form the lubrication film between the blank and die cavity, then the friction between these contact surfaces can be uniformed and decreased via the lubrication film [28, 41, 42]. Nevertheless, this film is squeezed out and the nanoparticle may agglomerate with 0.1 mm/s forming velocity, and then the scatter of forming force is increased and the height deviation increases compared with these under dry condition. Therefore, the height derivation decreased when using the lubricant, besides, the earing is mainly caused by uneven grain deformation, and this unevenness is likely to occur in the case with high forming velocity. In conclusion, the obvious earing profile appears significantly in the case with 0.3 mm/s forming velocity and can be weakened by decreasing forming velocity and using the lubricant.

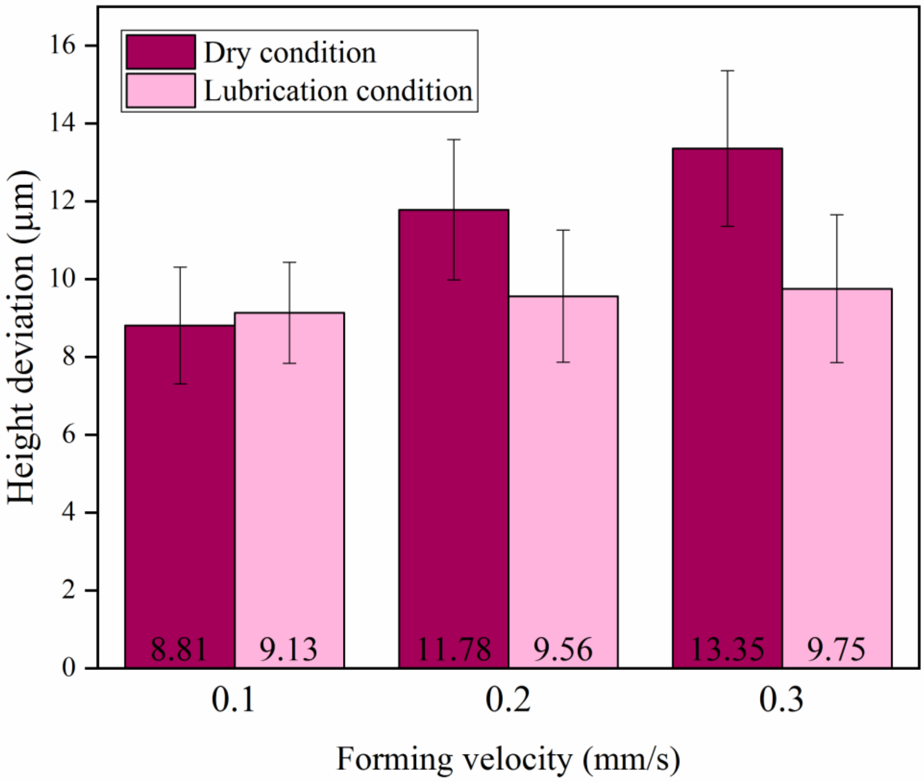


**Fig. 10.** The height deviation of drawn cup

The surface roughness is another crucial element to define the products' surface quality, and the tribological characteristic of the blank and tool interface can influence this element significantly. To evaluate the surface roughness, the mean roughness ($R_a$) defined by Eq. (6) and the value of the height of peaks and valleys ($R_z$) expressed as Eq. (7) are invented.

$$R_a = \left(\frac{1}{S}\right)\int_0^S \left|Z_{(x)}\right| d_x \tag{6}$$

$$R_z = R_p + R_v \tag{7}$$

where $S$ is the evaluation length, $Z_{(x)}$ is the height function of the measured profile, $R_p$ is the maximum peak height and $R_v$ is the maximum valley height from average line.

After the MDD, the sample's $R_a$ value increases from 0.15 μm and the $R_z$ also augments from 3.78 μm, which means the blank's surface becomes uneven and rough due to the deformation. As illustrated in Fig. 11, the $R_a$ value increased with a rise of the forming velocity under the dry condition, which means the product's surface is smoother and evener with the lower forming velocity. Fig. 12 shows the $R_z$ value after MDD process under the dry and lubrication conditions with different forming velocities. Under the dry condition, the variation of the maximum and minimum $R_z$ increases with the higher forming velocity. On the one hand, the friction is reduced by decreasing the forming velocity, then the surface's scratch can be diminished, and the quality can be improved with lower friction force [7, 11, 43, 44]. However, forming with higher velocity can generate larger flow stress simultaneously, which can break the surface grain boundary easily during the forming. Since the surface grains are less restricted in contrast with the inner grains, the scatter of the surface grain deformation rises because of the high strain rate and flow stress. Furthermore, the impact of the flow stress on the surface quality is more significant than the impact of the friction force, when alter the forming velocity [45-47]. Therefore, decreasing the forming velocity can improve the micro product's surface quality under the dry condition.

To decrease the friction in the MDD, the 4% $TiO_2$ nanoparticle lubricant was dipped in the die cavity. In contrast with the dry condition, the $R_a$ and $R_z$ values decreased when the forming velocity was higher than 0.1 mm/s, and these values reduced more significantly with the higher forming velocity under the lubrication condition. However, compared with the dry condition, the $R_a$ value increases from 0.4 to 0.61 µm and the $R_z$ value increases from 5.58 to 5.91 µm, when the forming velocity is 0.1 mm/s. The trends of the thickness's variations are similar under the dry and lubrication conditions. Namely, the cup mouth is thick, then the thickness reduces significantly by moving toward the cup bottom and increases slightly at the cup's bottom [6, 48, 49]. As shown in Fig. 13, the nanoparticle lubricant is dipped into the lower die, and then in MDD the modes of deformation are biaxial stretching at the punch nose (zone A), stretching zone at the punch corner radius (B), free drawing between the die and the punch (C), bending over the die profile (D) and radial drawing at the blank holding region (E). When the forming velocity is low, the extension area is mainly near the blank holder and punch radius (A, D), and the extension area of the cup wall (B, C) is relatively small compared with the bending area before the sample contacting the lower die wall. The blank's flow stress decreased when diminished the forming velocity, and the wall area's extension before the blank contacts the lower die is mainly caused by this flow stress. During the process, the punch's profile does not contact the blank all the time, when the punch moves downward, then bending area is larger and the extending wall area is smaller with the lower forming velocity before the blank contacts with the lower die wall. Furthermore, the lubricant affects more significantly on the area between the blank and lower die wall compared with the area between the cup's mouth and bottom due to the more contact area between the blank and lubricant [6, 22, 38]. Considering the open closed lubrication theory, the lubrication film can be divided into open and close pockets (CLPs) lubrication, which also can be known as dynamic and static lubrication pockets. When the forming load is applied on the contact surface between the lubricant and blank, the roughness peaks start to deform plastically, then the lubricant trapped into the close pocket can counteract the load pressure then reduces the friction. Besides, the lubricant in the close pockets can be squeezed out to the real contact surface, where the nanoparticle can be utilised to reduce the friction directly. In the case of open lubricant pockets (OLPs), which have a connection to the surface's edge, these valleys cannot keep the lubricant. The OLPs lubricant escapes and cannot support or transmit the forming load with increasing the normal pressure. Under the low forming velocity, the blank is abruptly contacted with the lower die and there is much lubricant to form the lubrication film in the small bending area. Besides, the material can squeeze the lubricant into the micro cup's mouth and bottom, which is easily to agglomerate with a large amount of lubricant left in such small space, then the agglomeration can result in a harmful effect on decreasing the friction and wear. Furthermore, under the higher forming velocity, the bending area is more vertical, and the extension area of the cup wall is larger. Therefore, the blank contact the lower die gradually and the contact area is larger compared with the lower forming velocity, then the lubrication film is evener, and more uniform. Above all, the micro product's surface quality can be improved by using the 4% $TiO_2$ nanoparticle lubricant under 0.2 and 0.3 mm/s forming velocities, and the efficiency of lubrication is improved through increasing the forming velocity

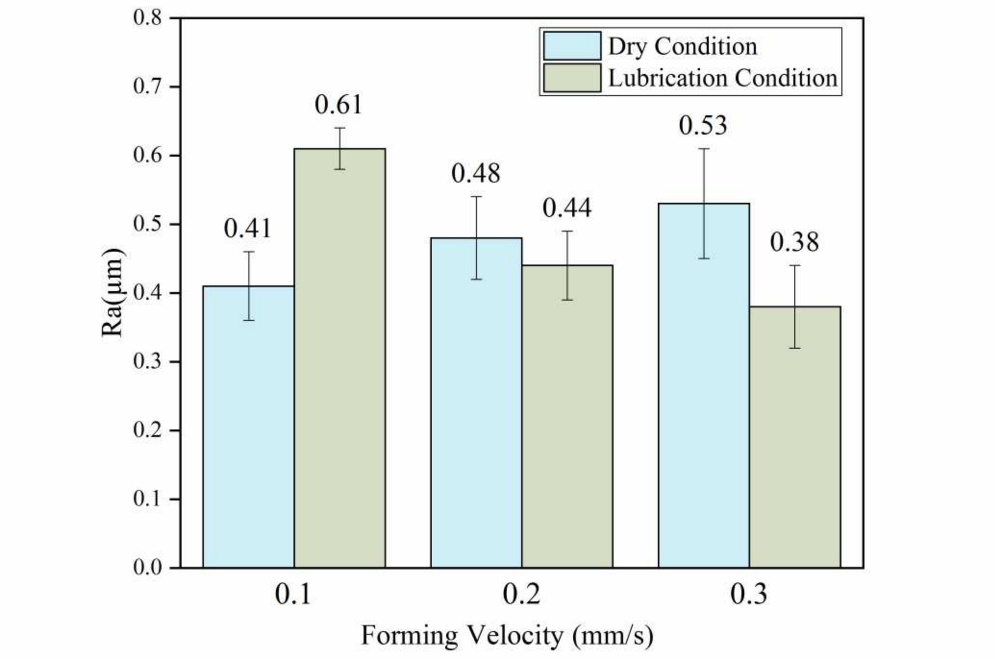


**Fig. 11.** The surface roughness by meaning of $R_a$

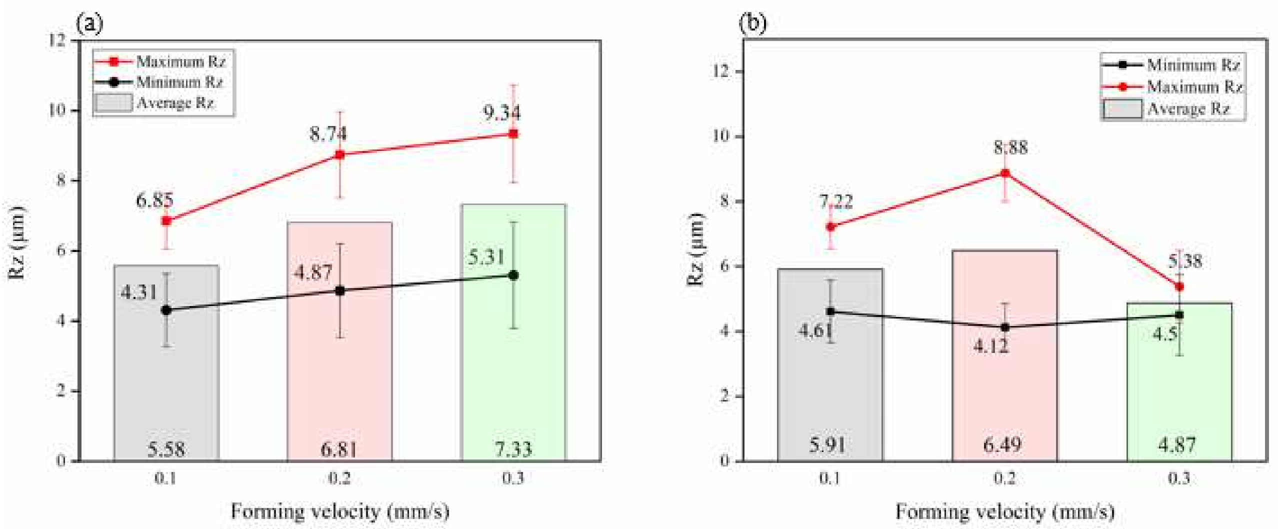


**Fig. 12.** The $R_z$ value comparison: (a) dry condition and (b) lubrication condition

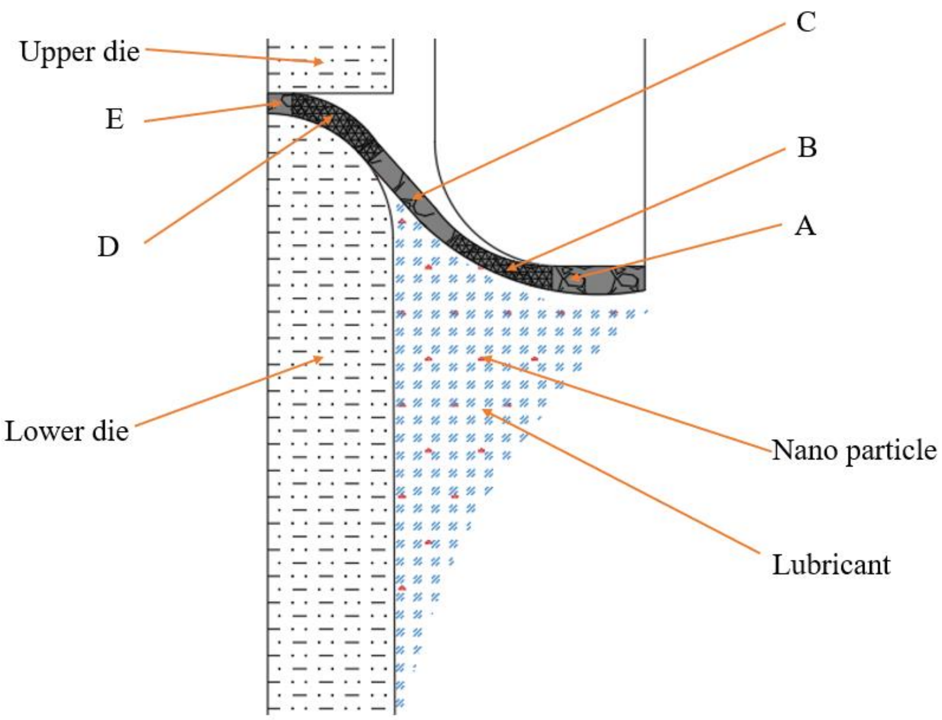


**Fig. 13.** Sketch of deep drawing configuration with hemispherical punch

# 4. Conclusion

This study presents an experimental study on forming micro austenite SUS301 cups with different blanking and forming velocities under the dry and nanoparticle lubrication conditions. The effects of forming velocity on drawing force, surface roughness and nanoparticle lubrication's efficiency were studied. The conclusions are follows:

1. The micro cup's profile can be modified by changing velocity under the dry and nanoparticle lubrication conditions. It was found that, the wrinkling value and the height derivation can be diminished when decreasing the forming velocity under the dry condition. Besides these values can be increased when the forming velocity is 0.1 mm/s under the lubrication condition due to the agglomeration.
2. The drawing force increased with an increase of the drawing velocity under the dry and nanoparticle lubrication conditions. The increase was significant in the case of setting the forming velocity higher than 0.1 mm/s. Besides the drawing force was reduced by utilising the nanoparticle lubricant when the forming velocity is 0.2 and 0.3 mm/s. However, the force increased under the nanoparticle lubrication condition with 0.1 mm/s forming velocity.

3. The surface roughness was considerably improved by utilising the nanoparticle lubricant. Under the dry condition, the surface became rough when increased the forming velocity. Furthermore the efficiency of nanoparticle lubricant increases with a rise of drawing velocity when the velocity is higher than 0.1 mm/s, and this lubricant can be agglomerated with 0.1 mm/s forming velocity.

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# Figures

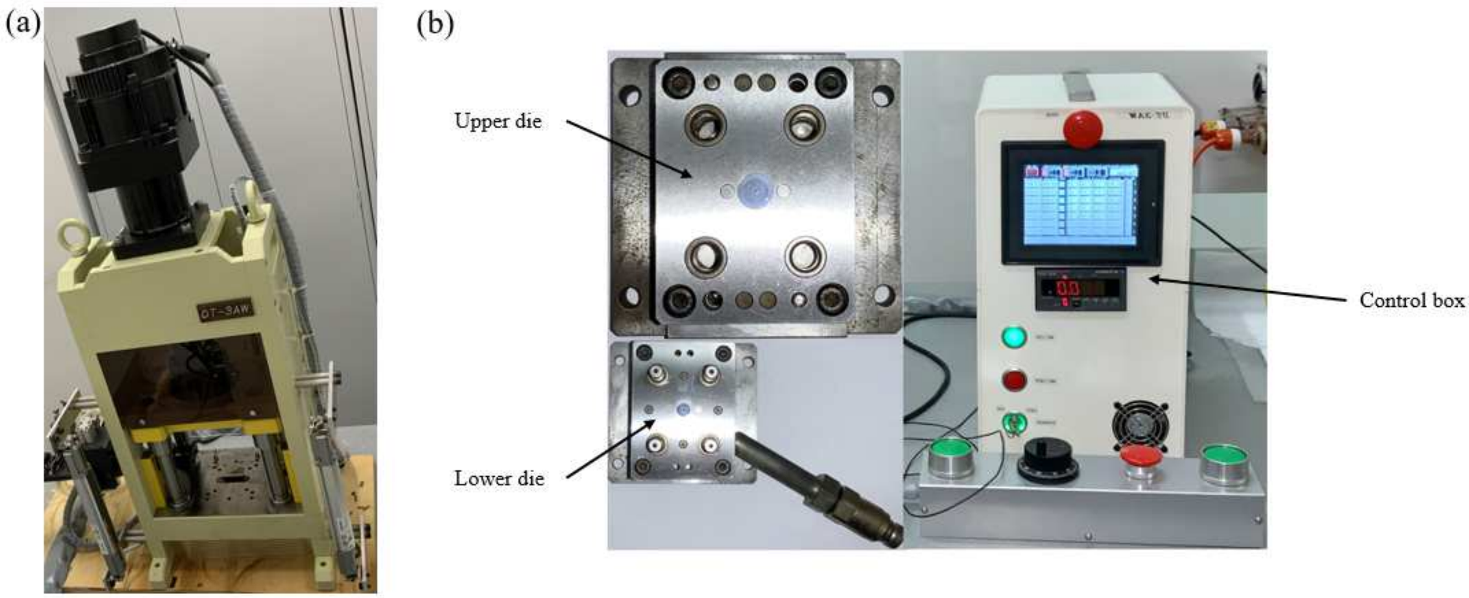


**Figure 1**

MDD apparatus. (a) Press machine DT-3AW; (b) MDD die set and control box

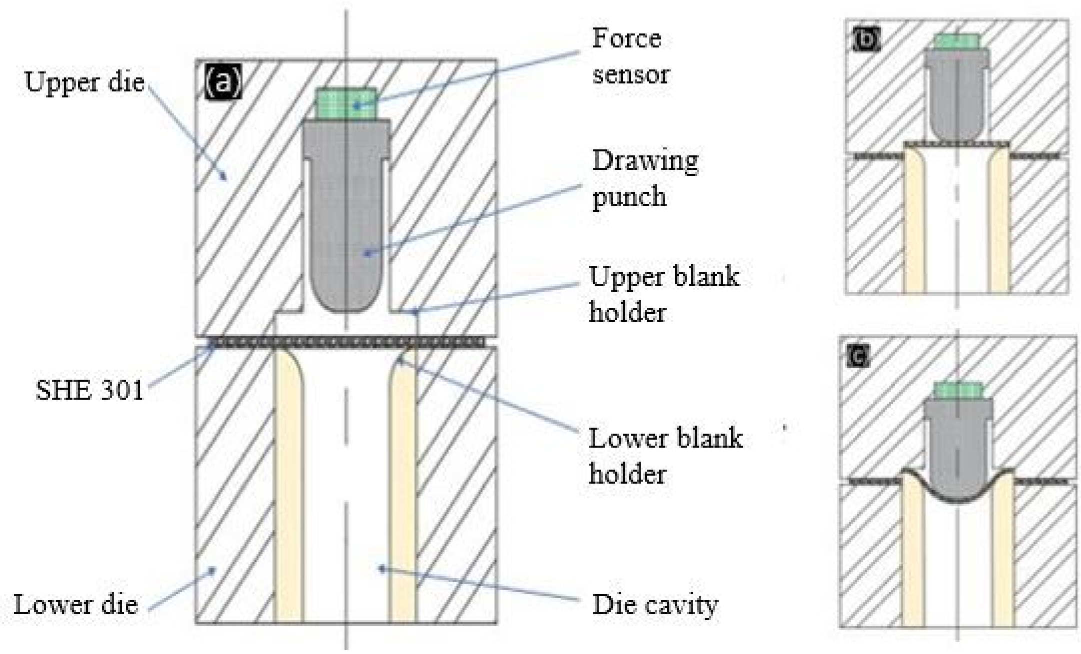


**Figure 2**

Schematic of MDD processes: (a). Initial stage of MDD, (b) Blanking stage of MDD, (c) Forming stage of MDD

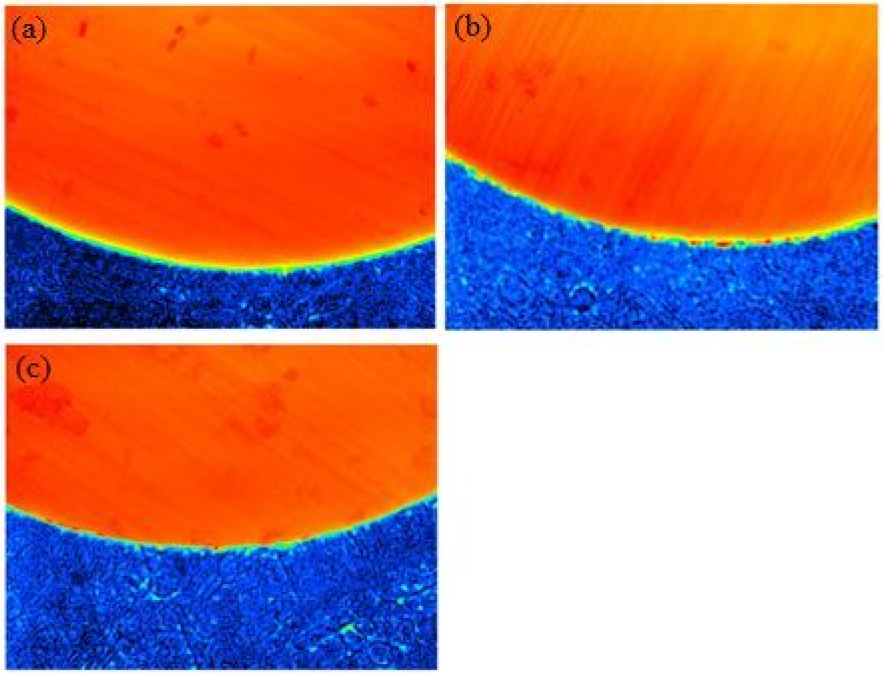


**Figure 3**

The blank edge of specimens under different blanking velocity: (a) 0.1 mm/s blanking velocity, (b) 0.2 mm/s blanking velocity, and (c) 0.3 mm/s blanking velocity

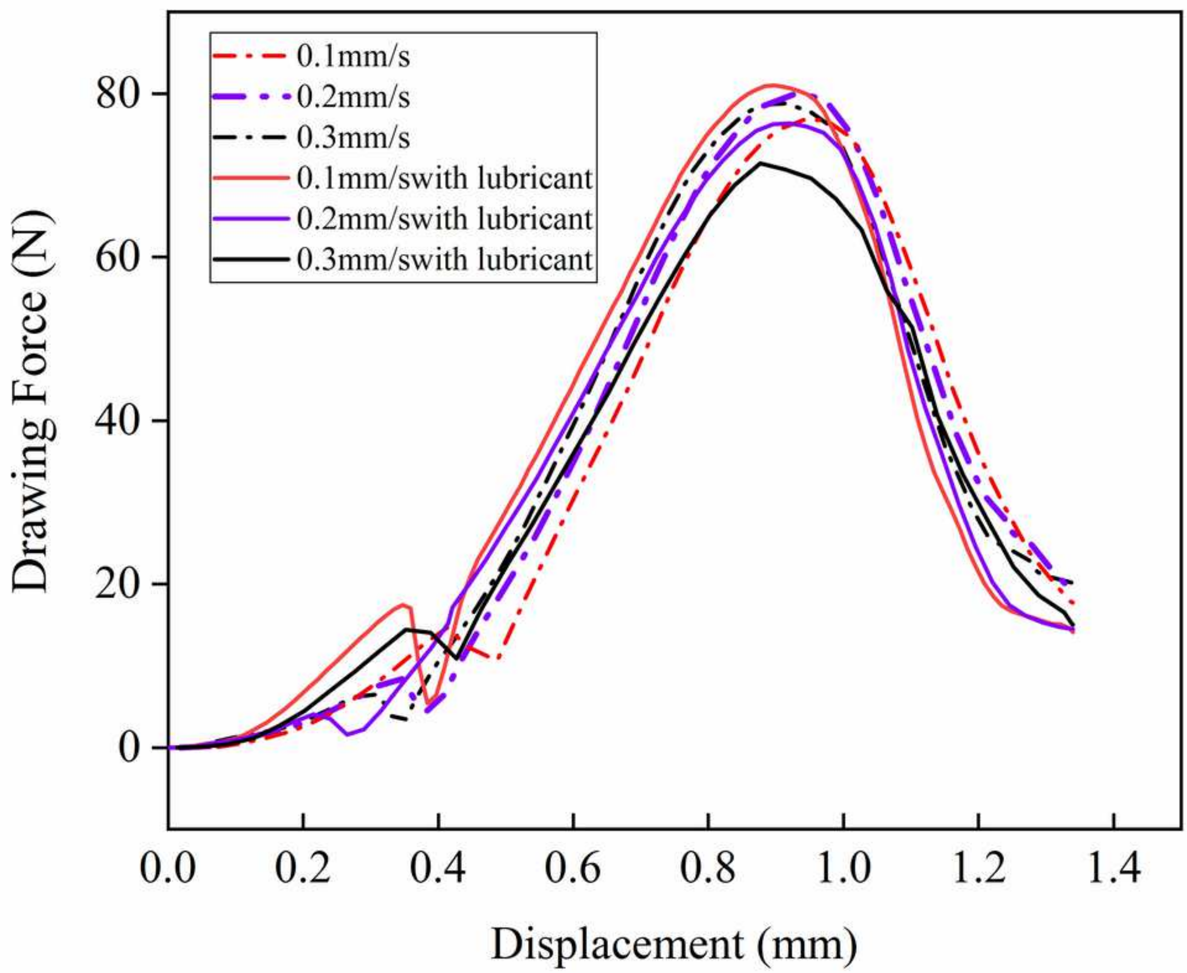


**Figure 4**

Drawing force-displacement curve with different forming velocities

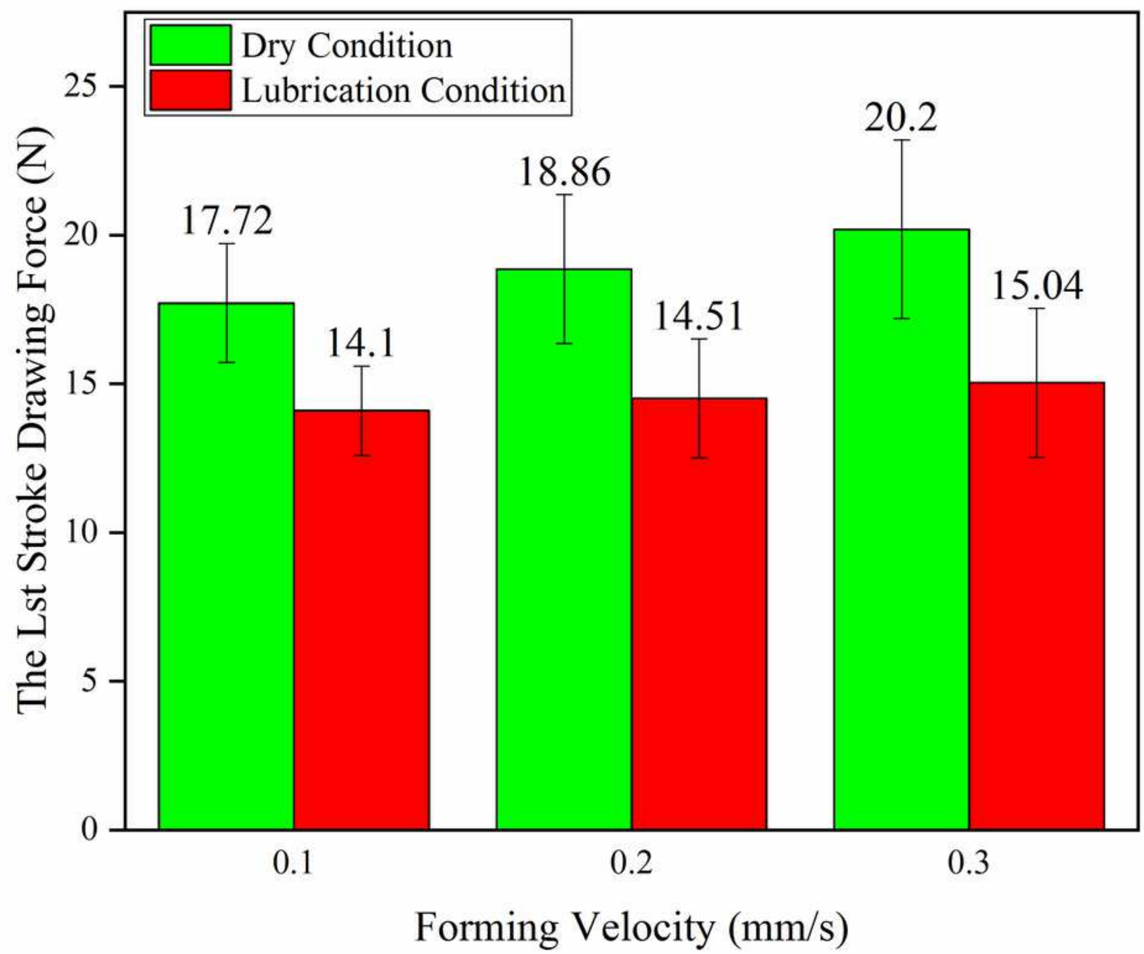


**Figure 5**

The last stroke drawing force comparison

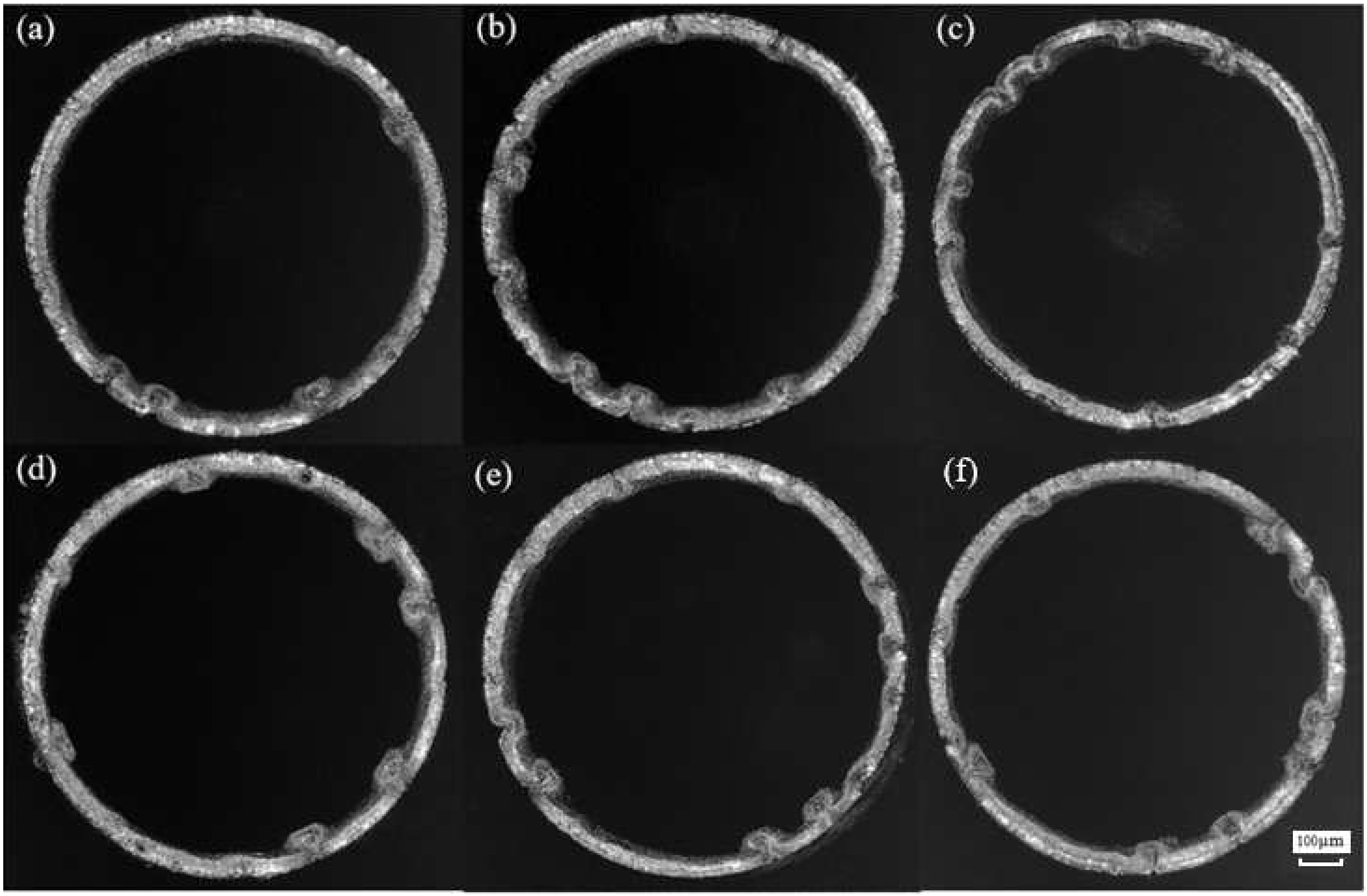


**Figure 6**

Drawn cups' mouth view in different forming velocities: (a) 0.1 mm/s in dry condition, (b) 0.2 mm/s in dry condition, (c) 0.3 mm/s in dry condition, (d) 0.1 mm/s in lubrication condition, (e) 0.2 mm/s in lubrication condition, and (f) 0.3 mm/s in lubrication condition

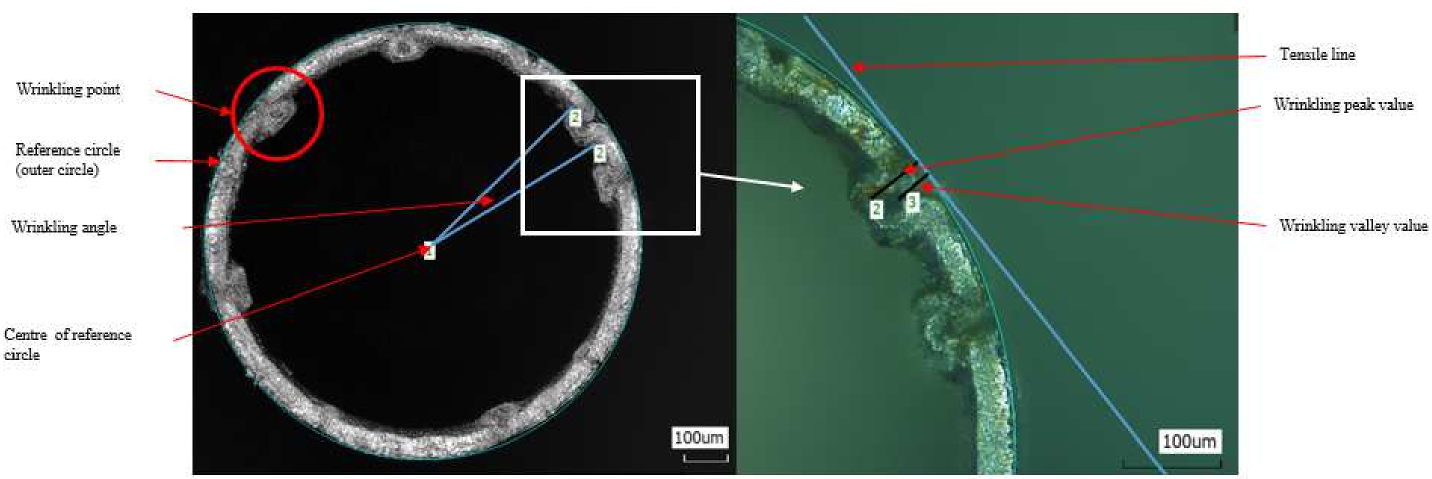


**Figure 7**

Wrinkling measurement of drawn cups

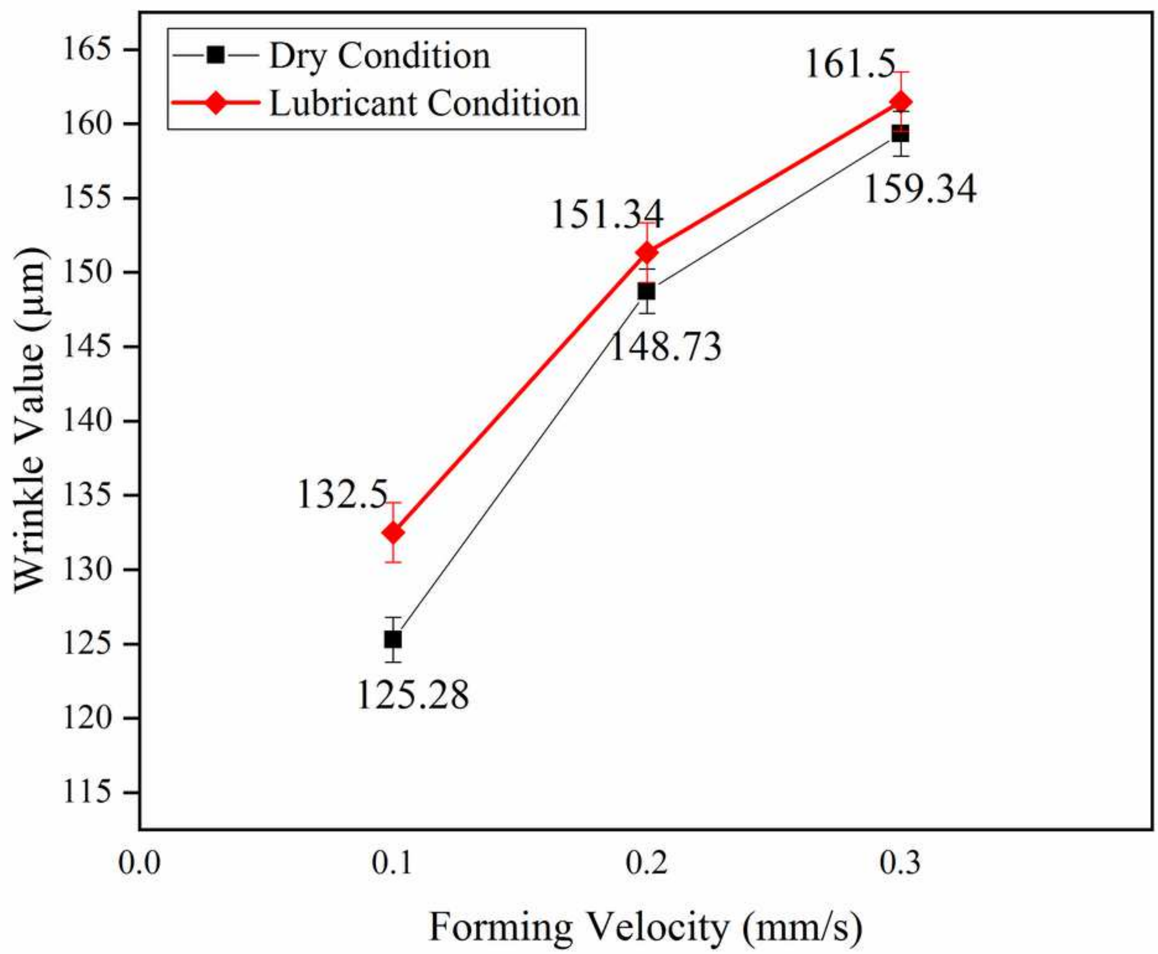


**Figure 8**

The wrinkling value of drawn cups

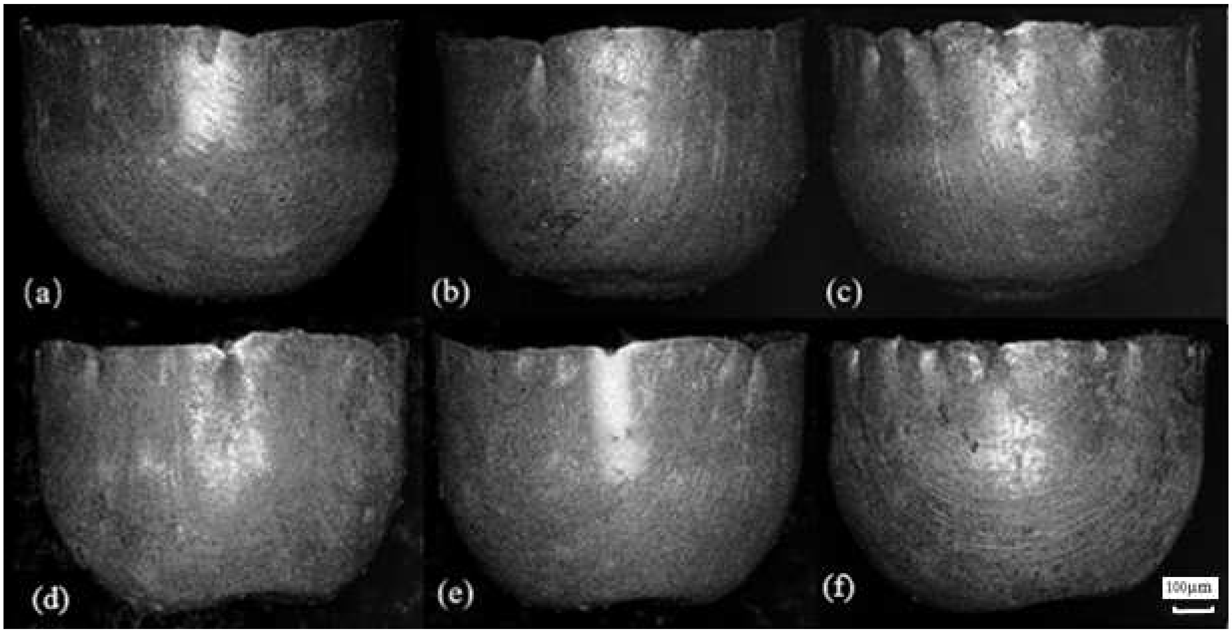


**Figure 9**

Drawn cups’ side-view in different forming velocities: (a) 0.1 mm/s in dry condition, (b) 0.2 mm/s in dry condition, (c) 0.3 mm/s in dry condition, (d) 0.1 mm/s in lubrication condition, (e) 0.2 mm/s in lubrication condition, and (f) 0.3 mm/s in lubrication condition

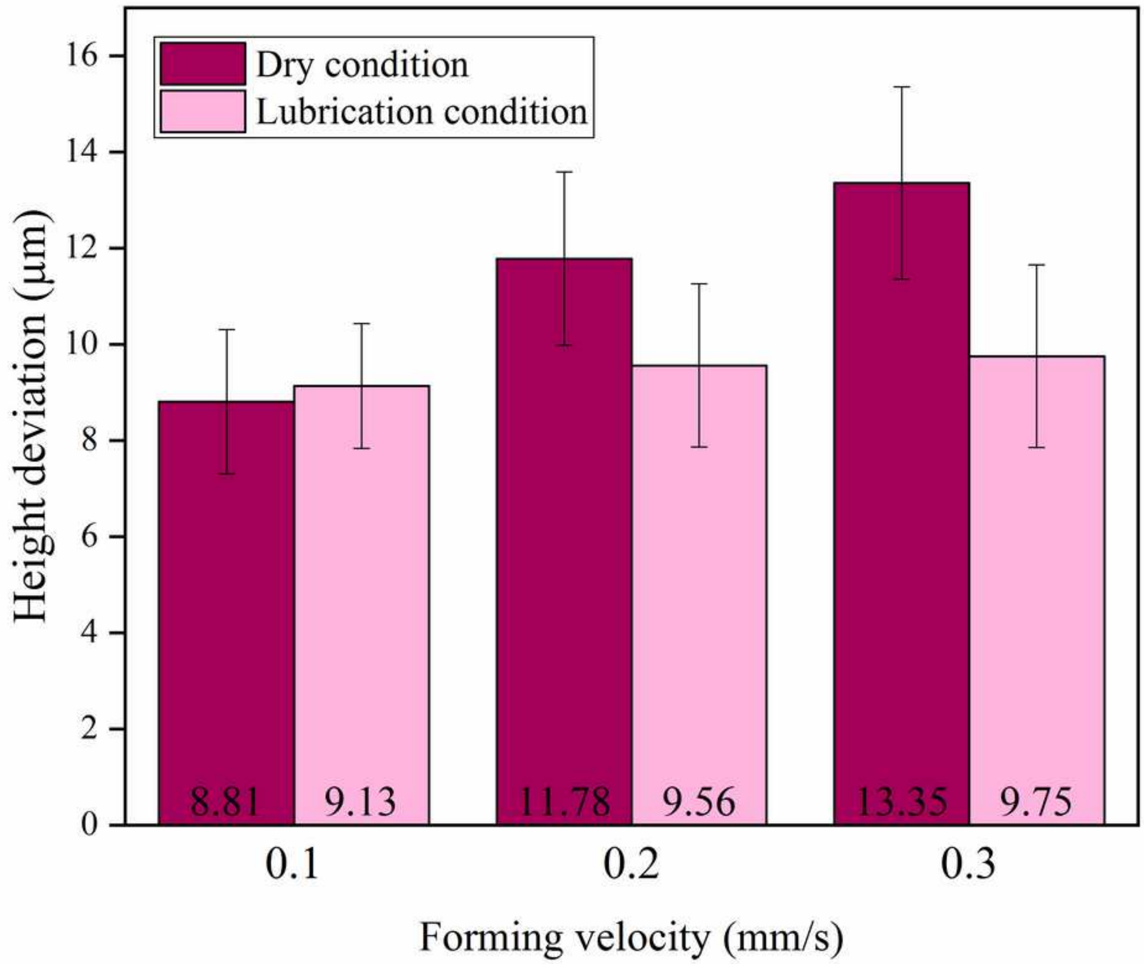


**Figure 10**

The height deviation of drawn cup

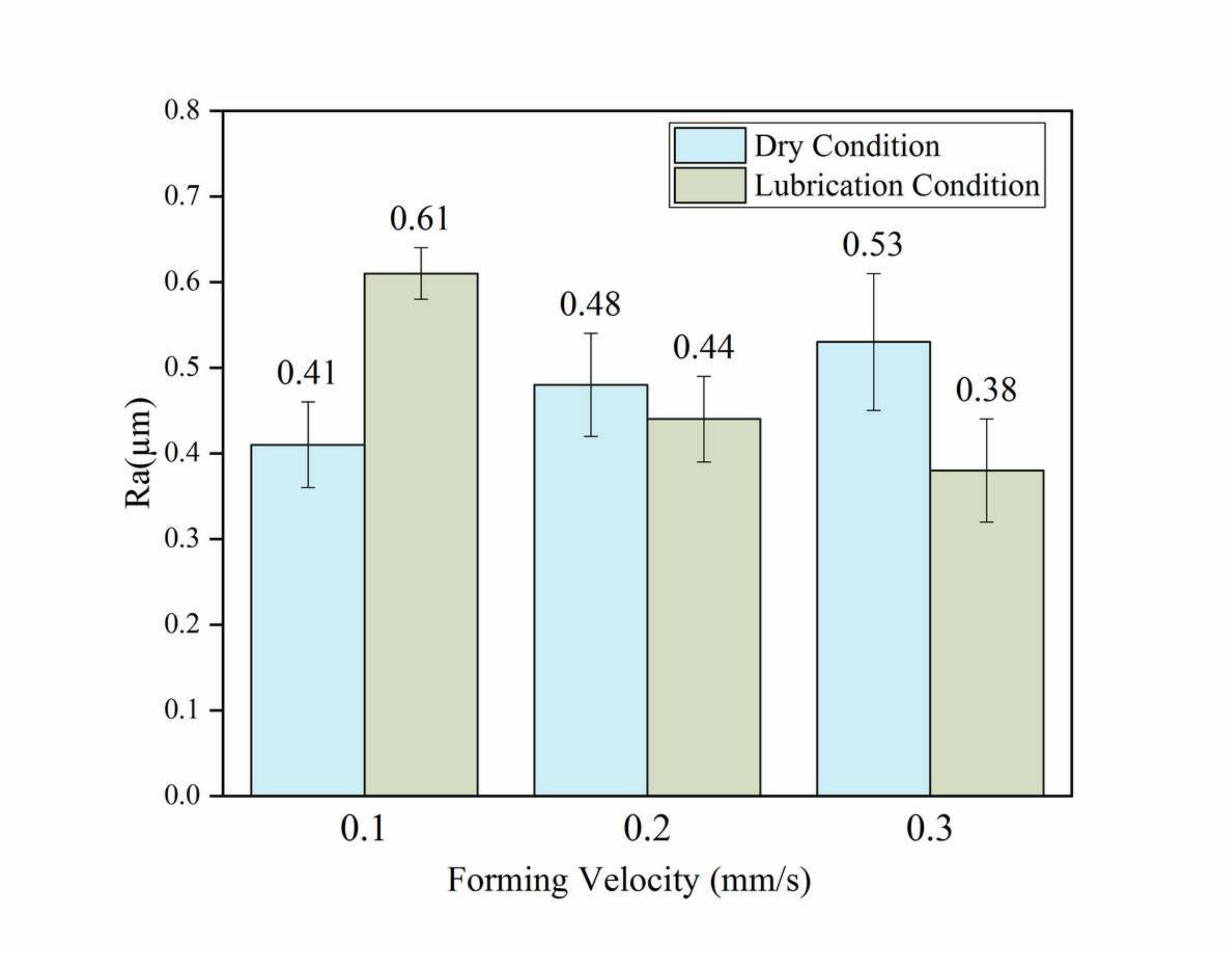


**Figure 11**

The surface roughness by meaning of Ra

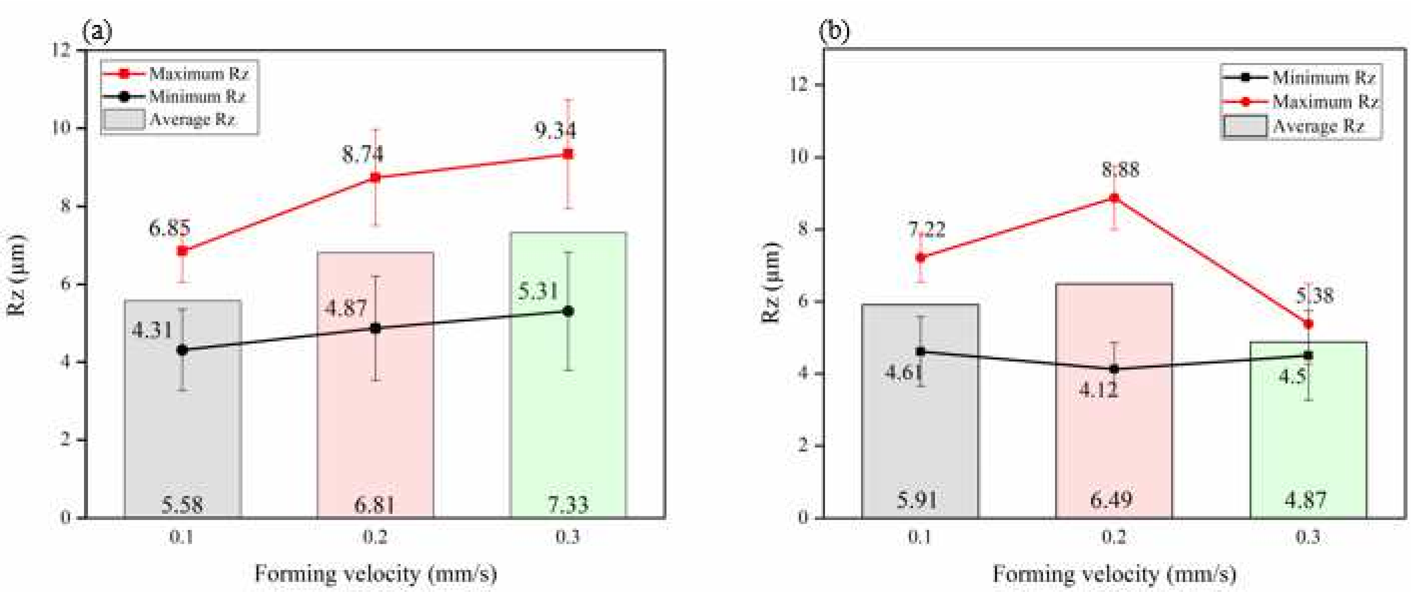

**Figure 12**

The Rz value comparison: (a) dry condition and (b) lubrication condition

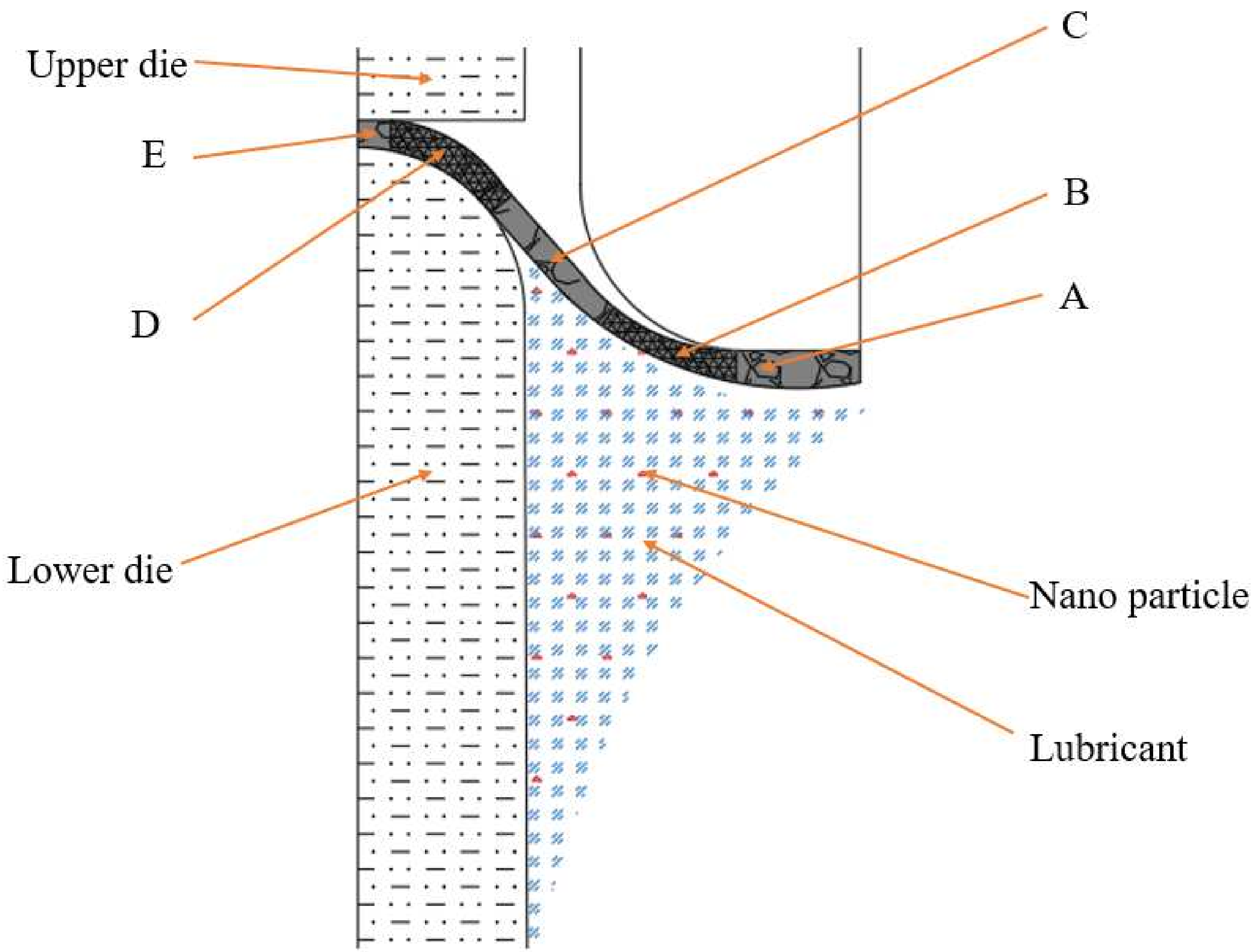


**Figure 13**

Sketch of deep drawing configuration with hemispherical punch