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ORIGINAL ARTICLE

Formability evaluation of a pure titanium sheet in the cold incremental forming process

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Abstract Owing to its ability to deform a sheet metal locally, the single point incremental forming (SPIF) process produces larger deformations as compared to the conventional forming processes. In the present study, we investigated the effect of some process parameters – pitch, tool diameter, feed rate and friction at the interface between the tool and blank – on the formability of a commercially-pure titanium sheet. Trends between the process parameters and formability are presented in this paper.

Keywords Incremental forming · Formability · Process parameters

1 Introduction

Along with the conventional stamping processes, which are now-a-days still used in the mass production of various products, several dramatic changes in the last few decades have occurred in order to satisfy many new relevant and prevalent market demands. The production of customized products, the increasing demand of process flexibility and the necessity to reduce the time to market the products are probably the most significant requirements of the present era. On the other hand, metal stamping processes have traditionally been characterized by the relevant equipment capital and the tooling cost. For these reasons, the industrial applications have to be economically justified with a large-scale production. Furthermore, stamping cannot fully satisfy the demand of flexibility.

The aforementioned considerations clearly show that the current metal stamping processes may maintain a relevant role in the modern production routings only if cheaper and more flexible technologies are developed. A great deal of research is being carried out in order to achieve such objectives. In the last few years, many sheet metal forming techniques have been under study so as to develop the novel forming processes characterized by high flexibility such as laser forming, water-assisted forming and single point incremental forming (SPIF) [1–6]. Among these innovative processes, SPIF has been studied intensively.

In the simplest form of the SPIF process, the final component shape is determined by the relative movement of a small punch with respect to the blank rather than the die shape. This process is usually carried out on CNC machines where it is possible to assign and control the punch movement according to the fixed paths [4–7]. The process has two variants: (1) Single point negative incremental forming (SP-NIF), and (2) single point positive incremental forming (SP-PIF). In the latter, the blank is supported with a die that increases the probability to produce parts with sharp corners [8].

Its flexibility and low-cost tooling renders SPIF more economical than spinning, which had been considered as an economical process to produce axisymmetric components in small batches [9–10], In addition to this, the SPIF process can be employed for a variety of applications as found in the literature [11–14]:

- It is a very economical process for rapid prototyping.
- The process is capable to manufacture a variety of irregular-shaped components and highly customized medical products.

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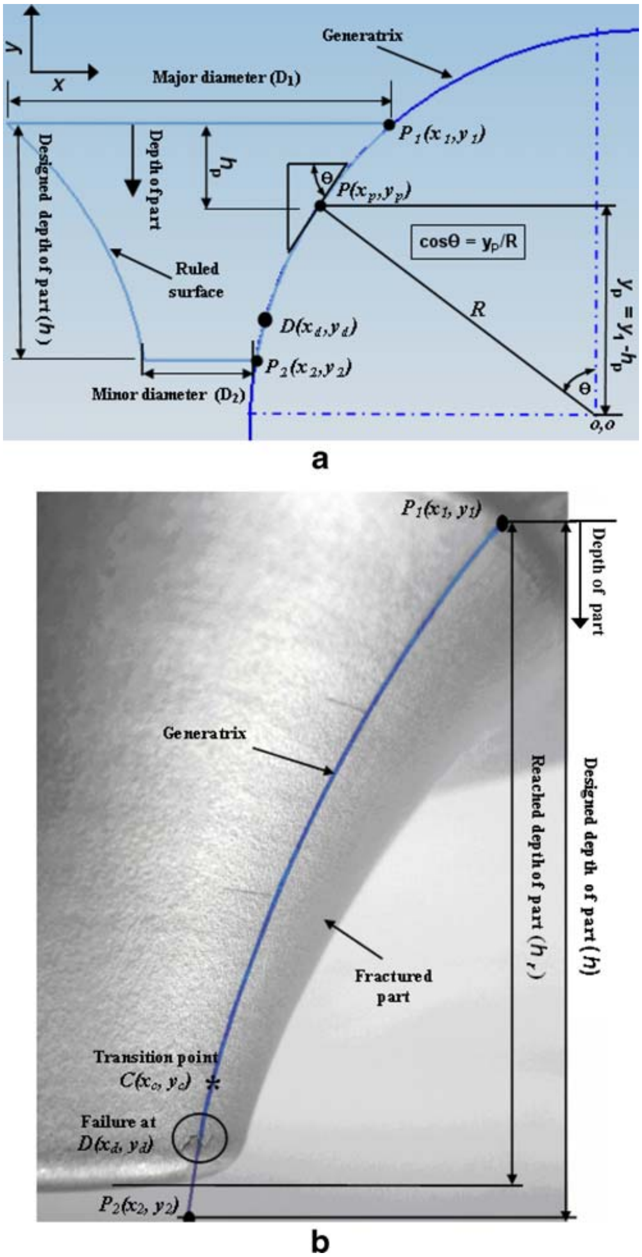

Fig. 1 Illustration of the formability test: (**a**) 2D view of the ruled surface, and (**b**) A section view of the fractured specimen formed to test the formability of an aluminum sheet [20]

– The method creates large regions of homogenous deformation and avoids the large stress and strain gradients. Due to this fact, a specimen formed by the process is considered to be more reliable to calibrate a void nucleation model than the tensile specimens.

Several studies have been carried out on the formability in SPIF [15–22]. Shim and Park [17] performed finite element and experimental analyses and concluded that the deformation imposed by the forming tool is confined to the vicinity of the contact area with the sheet. This shows that the formability in SPIF is not affected by varying the blank size. This was also verified by Strano et al. [18], who formed a series of cones by varying the base curvature and found that the formability remains unaffected. Kim and Park [19] investigated the effect of some process parameters on the formability of an aluminum sheet. However, they did not study the effect of horizontal feed rate. Both Strano et al. and Kim et al. drew forming limit curve (FLC) to represent the formability in SPIF. In the present study, however, the formability was defined as the maximum wall angle (θ_{max}, which is a practical forming parameter) that a sheet would endure without fracturing. The effect of most of the process variables on the cold formability of commercially-pure titanium (CP Ti) sheet has been addressed adequately. However, the effect of sheet thickness could not be investigated due to un-availability of sheets of different thicknesses. The varying wall angle conical frustum (VWACF) test, as reported in Hussain et al. [20–22], was employed in order to evaluate the formability (θ_{max}).

2 A brief introduction of the formability test [20]

As mentioned earlier, the varying wall angle conical frustum (VWACF) test was employed to determine the SPIF formability of CP Ti. This innovative method makes use of a curved-line-generatrix to generate a revolved surface whose wall angle varies continuously (see Fig. 1). The surface is expected to fracture on a point $D(x_d, y_d)$ before reaching the designed depth. According to [20], $C(x_c, y_c)$ is a transition point after which the actual thickness of the part begins to disobey the sine law. Hence, the wall angle on this point is regarded as θ_{max}.

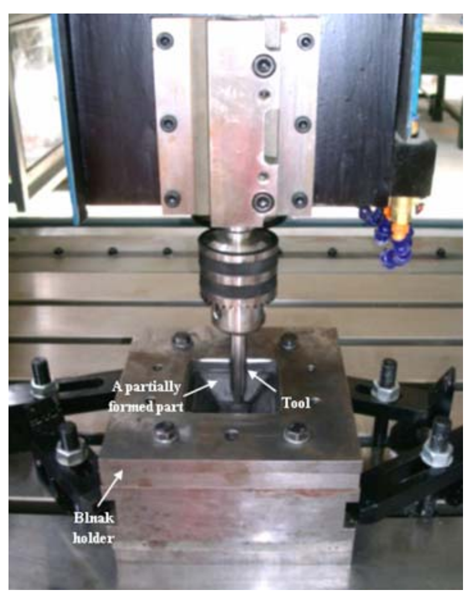

Fig. 2 The experimental set-up

The wall angle θ_p and thickness t_p on an arbitrary point $P(x_p, y_p)$ can be computed by using the following relations (see [20] for detail):

$$\theta_p = \cos^{-1}\left(\frac{y_p}{R}\right) = \cos^{-1}\left(\frac{y_1 - h_p}{R}\right) \tag{1}$$

$$t_p = t_0.\frac{y_p}{R} = \frac{t_0}{R}\left(y_1 - h_p\right) \tag{2}$$

The depth h_p of the point $P(x,y)$ is measured from the fractured part, while R,t_0 and y_1 are known values.

3 Experiments

3.1 Material and experimental set-up

The CP Ti sheet with 0.99 mm thickness was used as the experimental material. Its composition and mechanical properties are given as follows:

Chemical composition							*Mechanical properties*		
Fe (%)	C (%)	N (%)	H (%)	O (%)	Others (%)	Ti (%)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
0.20	0.08	0.03	0.015	0.18	0.4	99.1	230	350	40

Figure 2 shows the experimental set-up employed for the current work. A CNC milling machine tool was used as the experimental equipment, and spiral tool path was used in order to control the tool motion. Since the machine tool was equipped with an electric spindle, it could not provide enough force to deform the CP Ti sheet. Therefore, a special tool holder was designed to hold the forming tool using which the tool could be given sliding motion only. The blank 140×140 *mm* was held at the periphery with the blank holder, and deformed with the surface-hardened (60–65 HRC) HSS tool.

3.2 Lubrication

In another study by Hussain and Gao [23], it was found that a large contact force between the tool tip and CP Ti sheet squeezes the organic lubricants - oils, greases, etc. - out from their interface. Therefore, an inorganic lubricant (98.5% pure MoS_2 powder with medium grain size) mixed with grease was used as a lubricant. Moreover, in order to ensure its presence at the interface between the tool tip and blank, anodization of the blank was found to be an essential prerequisite. The porous film of titanium oxide with the average pore diameter and film thickness of 7.275 μm and 24.13 μm, respectively, was developed on the blank surface. The paste, which was prepared by compounding the MoS_2 powder and petroleum jelly in the proportion of 4:1, respectively, was rubbed on the oxide film in order to provide sufficient lubrication (see Fig. 3).

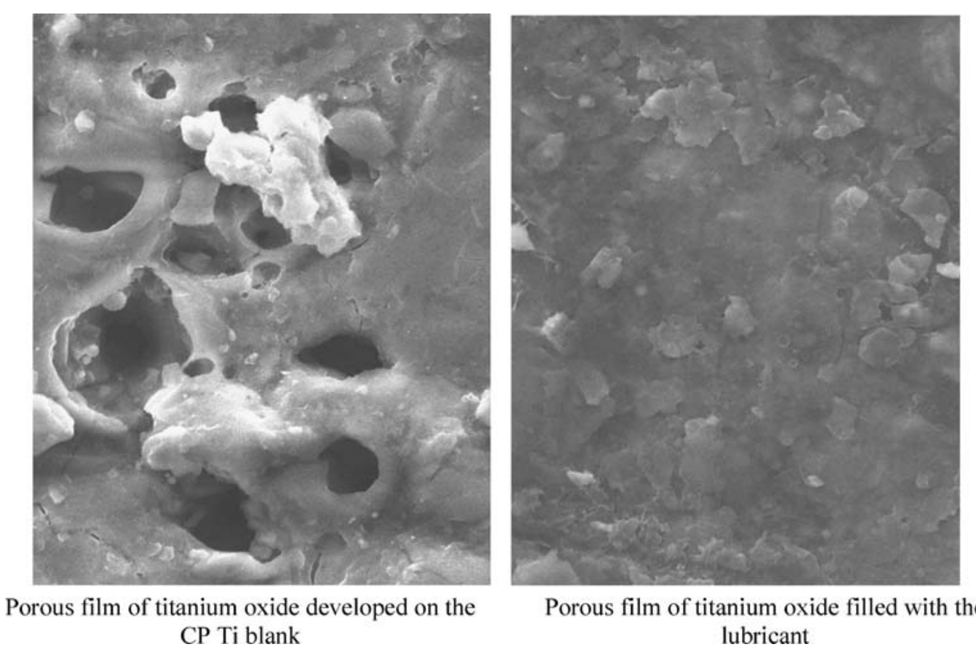

Fig. 3 The lubrication method [23]

3.3 Experimental procedure

An arc of a circle having the radius of 115 mm, and the Cartesian co-ordinates of (−70.9, 90.544) and (112.5, 23.848) at the initial and end points, respectively, was selected as a generatrix to design a conical frustum with continuously varying wall angle. Because the CP Ti sheet was expected to show low formability, a curve with the slope ranging form 38–78°, instead of 0–90°, was selected in order to reduce the blank size and forming time. Required object modeling and too-path programming were carried out in the commercial CAD/CAM software '*UG NX*-3'. The blanks were anodized as discussed in the preceding section.

The design of experiments in order to investigate the effect of some process parameters has been shown in Table 1. All of the experiments were conducted with the same test specimen design, lubricant and tool hardness. All the specimens, one is shown in Fig. 4, were formed to fracture with the hemispherical head tools. The forming of the specimens was observed closely, and the machine tool was stopped manually as soon as a specimen fractured. In fact, a fracture produced sound on hearing which the machine tool could be stopped. Thus, each specimen fractured in a controlled manner. A depth gauge was used to measure the depth of a specimen to any arbitrary point, and a dial gauge indicator was used as a thickness measuring instrument (see [20] for further detail).

In order to investigate the effect of friction at the tool/blank interface, specimens were formed under three friction conditions: (1) without rubbing any lubricant on the anodized blank (very high friction); (2) by rubbing the paste of graphite powder (static co-efficient of friction: 0.1) and grease on the anodized blank; (3) by rubbing the paste of MoS_2 powder (static co-efficient of friction: 0.05) and grease on the anodized blank. The specimens were formed with 12 mm tool diameter, 0.2 mm pitch and 1200 mm/sec feed rate.

Table 1 Design of experiments for some process parameters

Exp. #	[a]f [mm/sec]	[b]d [mm]	[c]p [mm]
1	2600	12	0.2
2	2600	12	0.75
3	2600	12	1.3
4	1200	12	0.75
5	4000	12	0.75
6	2600	8	0.75
7	2600	16	0.75

a: feed rate; b: tool diameter; c: pitch

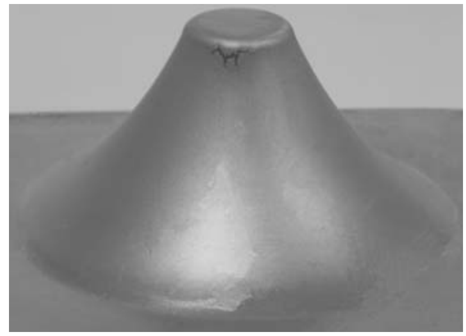

Fig. 4 A representative test specimen, whose wall angle varies along the depth, of the CP Ti sheet

4 Results and discussion

Figure 5 depicts the wall thickness profile of a specimen formed in the present study. This is evident from the figure that the thickness along the specimen decreases as the wall angle or depth increases. The actual thickness on the transition point '$C(x_c, y_c)$' is in good agreement with the analytical one. Thus, the wall angle on the point '$C(x_c, y_c)$' was regarded as θ_{max}. It is to be seen that the transition point locates very close to the fracture point '$D(x_d, y_d)$'. While, in an aluminum specimen formed in a previous study [20], the transition point locates well below the fracture point (see Fig. 5). It shows that, in this specific test, CP Ti does not exhibit visible localized necking prior to fracture. This result was also verified for a number of

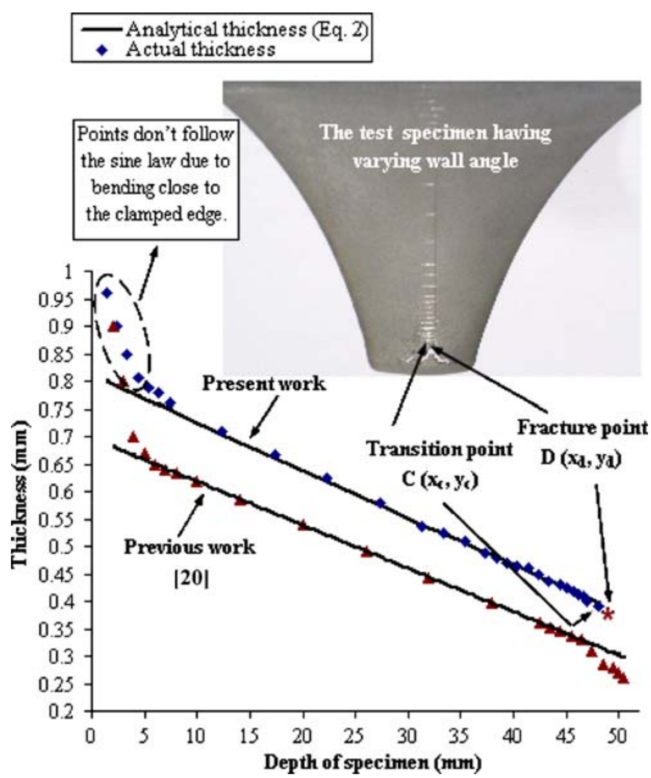

Fig. 5 Wall thickness profile of a CP Ti test specimen

specimens formed with various combinations of the process parameters given in Table 1. This may be due to the reason that CP Ti has higher strength than aluminum. In addition, as the forming depth increases, the deformation force increases that may cause a sudden fracture. However, a part having fixed wall angle shows localized necking prior to fracture, because the deformation force is kept relatively constant by keeping the wall angle constant.

In order to check repeatability of the results, two samples for each test were produced, the maximum variation in the results was found to be ±0.2%. Based on the average results, the effect of various process variables on the formability of CP Ti sheet is discussed in the next sections:

4.1 Pitch

The experiments were conducted at the constant feed rate and tool diameter of 2600 mm/min and 12 mm, respectively. The pitch value was varied from 0.2 mm to 1.3 mm. The maximum value of θ_{max} is 65° at 0.2 mm pitch, and the minimum value is 60.7° at 1.3 mm pitch (see Fig. 6a). As the matter of fact, at large pitch values, the metal is partially deformed by the forming tool and partially by pulling. Thus, the deformation no more remains localized and the metal exhibits low formability. It was also found that by increasing the pitch, striated surfaces with large roughness values are formed. The formability obeys the linear law with negative slope.

4.2 Feed rate

The test specimens were formed at the constant pitch and tool diameter of 0.75 mm and 12 mm, respectively. This is evident from Fig. 6b that the value of θ_{max} varies from 64.33° to 61.66° as the feed rate is increased from 1200 mm/min to 4000 mm/min. The formability obeys the quadratic law. The decrease in formability from 2600 mm/min to 4000 mm/min is higher than that from 1200 mm/min to 2600 mm/min. This trend can be attributed to metal work hardening due to increased feed rate.

4.3 Tool diameter

In order to investigate the influence of tool size on the formability, the tool size was varied over three levels, i.e., 8 mm, 12 mm and 16 mm. While, feed rate and pitch were maintained at 2600 mm/min and 0.75 mm, respectively. The maximum and minimum formability values were found to be 65.6° and 63.1° at 8 mm and 16 mm diameters, respectively. This is obvious form Fig. 6c that the formability is governed by quadratic law, and the formability decreases as the tool diameter increases. In fact, an increase in the tool size increases the contact area, and thus the deformation does not remain localized as compared to that caused by a small-sized tool. Due to this reason, the formability decreases as the tool diameter increase. The drop in formability from 8 mm to 12 mm diameter is significantly large. However, the drop in formability form 12 mm to 16 mm diameter is very minor. It is to be seen that the formability remains almost constant for a specific range of 14 –15.5 mm tool diameter, and begins to increase after 15.5 mm tool diameter. It can be inferred that there may be some combined effect of tool diameter (d) and pitch (p) on the formability, i.e., the effect of d/p. However, this will be studied in future.

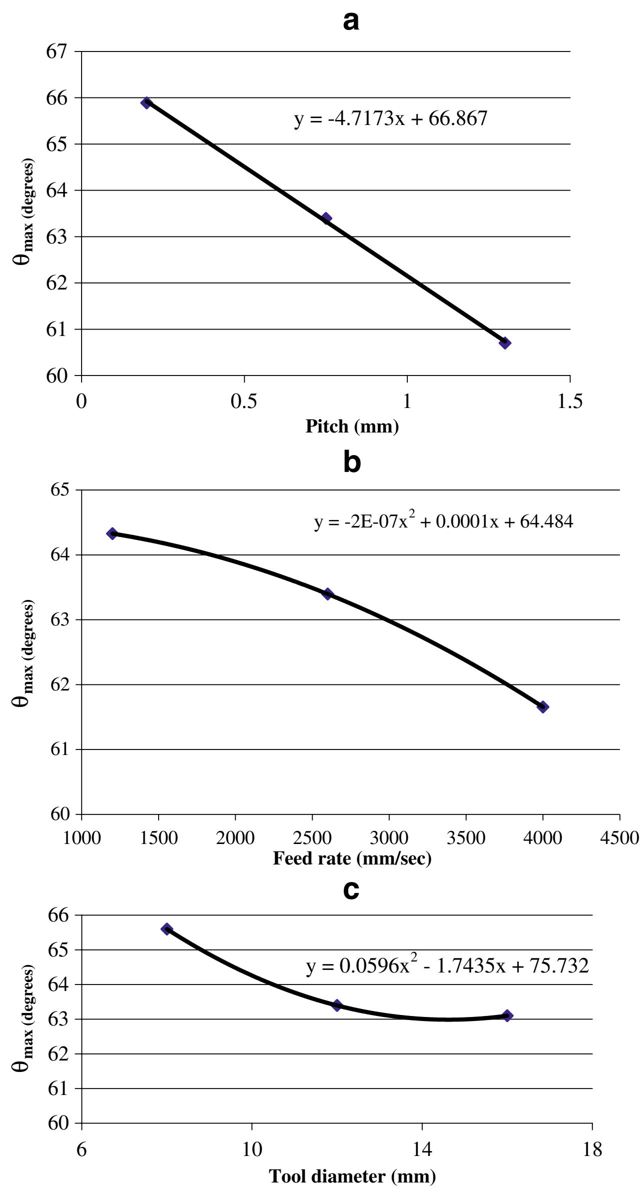

Fig. 6 The effect of: (**a**) pitch, (**b**) feed rate, and (**c**) tool diameter on the formability of CP Ti

4.4 Friction at the tool/blank interface

As discussed in Section 3.3, specimens were formed under three friction conditions. Figure 7a presents the results

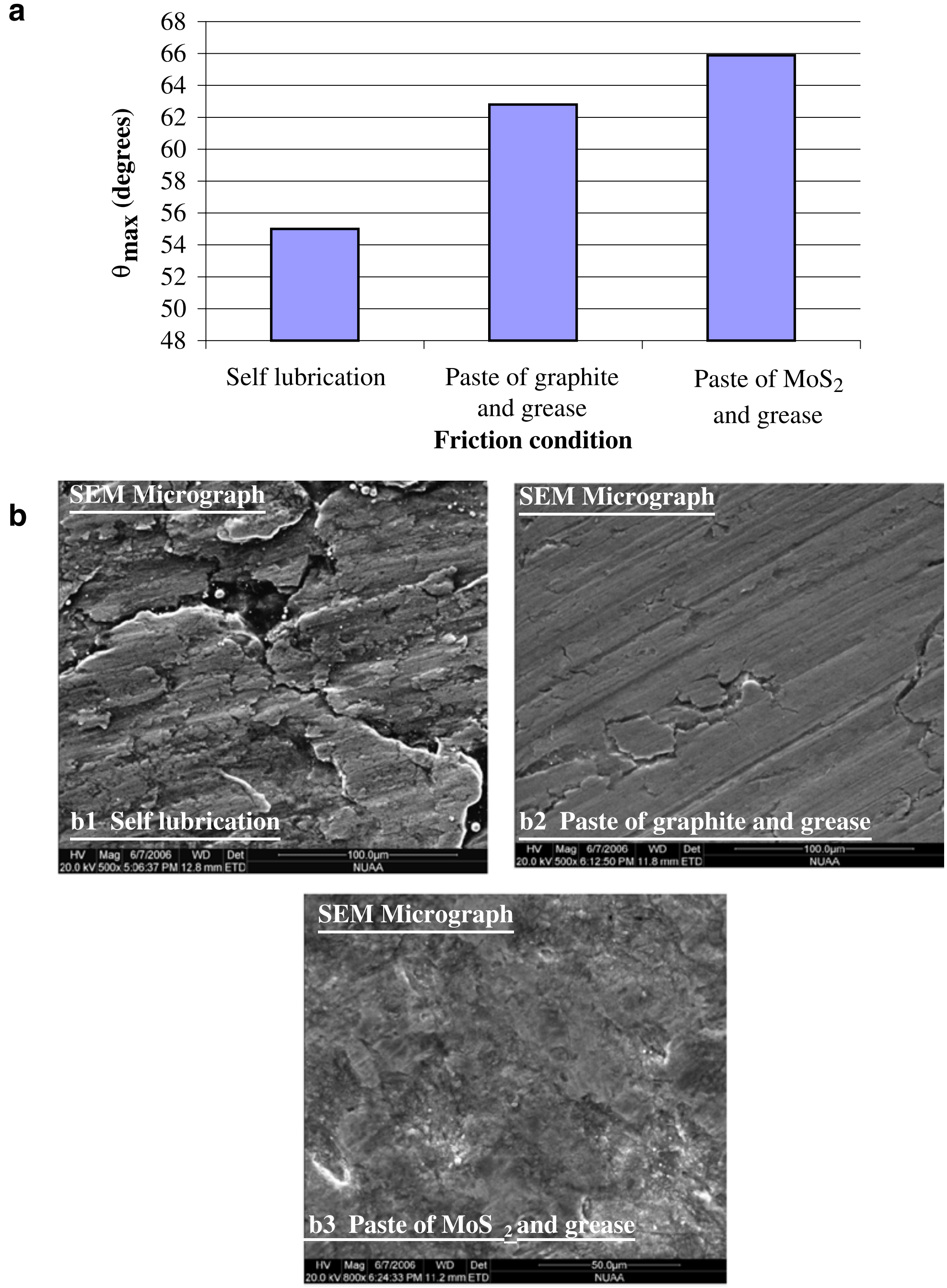

Fig. 7 Effect of friction at the tool/blank interface on: (**a**) the formability of CP Ti, and (**b**) the surface quality

showing the effect of friction at the tool/blank interface. When the sheet was formed without using any lubricant (self lubrication), i.e., very large friction, the blank material adhered to the tool tip, and the specimen surface was peeled off (see Fig. 7b). The specimen fractured after forming the depth of 27 mm only, and θ_{max} was found to be 55°. The specimen formed by using the paste of graphite and grease as lubricant showed relatively better surface quality. But, striations and sticking of blank material to the tool tip was observed again. The specimen could be formed to the depth of 40 mm, and the formability was found to be 62.8°. The specimen that was formed by using the paste of MoS_2 powder and grease showed the best surface quality (no striations on specimen surface and metal peeling), and no metal sticking to the tool tip was observed. This is also clear from Fig. 7(b3) which shows the presence of lubricant (MoS_2 matrix) on the specimen surface. The forming depth (44.6 mm) and θ_{max} (65.88°) were found to be the maximum among those obtained by any other specimen.

Although the CP Ti parts can be formed under high friction conditions, the surface quality is very poor. Moreover, high friction at the tool/blank interface decreases the formability of the CP Ti sheet. Therefore, it can be concluded that friction at tool/blank interface produces poor quality components and does not enhance the formability. Based on the metal behavior observed during experiments, it is expected that friction at the tool/blank interface may not improve the formability even if the forming tool is rotated.

5 Conclusions

The present study was carried out in order to investigate the effect of some process parameters on the formability (θ_{max}) of a commercially-pure titanium sheet. The results obtained from the study are summarized as follows:

1) The formability decreases linearly as the pitch increases.
2) An increase in the feed rate decreases the formability. The relation between feed rate and θ_{max} is a quadratic curve. Within the investigated range, the drop in formability is higher when the feed rate exceeds 2500 mm/min feed rate than drop in formability before 2500 mm/min. It means that the CP Ti sheet shows high work hardening at high feed rates.
3) By increasing the tool diameter, the formability decreases. The relation between the tool diameter and θ_{max} is governed by a quadratic law. Under investigated forming parameters, θ_{max} decreases significantly when the tool diameter is increased from 8 mm to 12 mm. However, from 12 mm to 16 mm tool diameter, the decrease in θ_{max} is minor.
4) Friction at the tool/blank interface does not increase the formability of CP Ti sheet. The higher the friction, the poorer the surface quality will be.

6 Future work

1) The effect of tool diameter to pitch ratio (d/p) on the formability of CP Ti sheet will be investigated in future. For this purpose, the ratio 'd/p' will be maintained at a constant value, while the tool diameter will be varied.
2) The sheet thickness may affect the formability, which will be studied in future.

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