Int J Adv Manuf Technol (2016) 87:2911–2923
DOI 10.1007/s00170-016-8665-6

ORIGINAL ARTICLE

A comprehensive experimental investigation on the influences of the process variables on warm incremental forming of Ti-6Al-4V titanium alloy using a simple technique

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Received: 18 September 2015 / Accepted: 22 March 2016 / Published online: 7 April 2016

Abstract The incremental forming has recently acquired a significant importance in various applications, such as automotive, aerospace, and medical industries. The present investigation is concerned with the warm incremental forming of Ti-6Al-4V titanium alloy. With this regard, the groove test was employed as a simple technique to study the effects of different variables, namely, the process temperature, the vertical pitch, and the tool diameter, on the forming limit diagram of the material, the springback, drawing depth, final temperature of the sheet, and the thickness variation of the product. The sheet temperature was the most important parameter affected by the interfacial friction and the other process variables. The experimental findings illustrated that the greater the vertical pitch and/or the tool diameter, the larger the formability and drawing depth of the sheet sample before its fracture. Moreover, decreasing the tool diameter and increasing the vertical pitch and the initial process temperature resulted in more thickness reduction. The actual process temperature simultaneously affected the elastic modulus and the flow stress of the component. However, the flow stress reduction due to the temperature rise overcame the elastic modulus decrease and, finally, the springback was lower at higher process temperatures.

Keywords Warm incremental forming · Groove test · Ti-6Al-4V titanium sheet · Formability · Temperature

1 Introduction

The incremental forming (IF) is one of new sheet forming methods which is extensively employed in various applications, such as automotive, aerospace, and medical industries. This technique possesses a significant flexibility for efficient production of components with complicated geometries. No expensive conventional die is needed for this process and, instead, by means of a tool, a special blankholder, and a CNC machine, the metal sheet is formed [1]. Since this operation is time consuming, it is usually used for forming prototypes or low-quantity productions.

Different parts of an incremental forming setup are the blank, the blankholder, the backing plate, and the forming tool. An IF operation, without using a negative die, is called single-point incremental forming (SPIF), where the tool is engaged with the sheet sample at just one side. When a positive die is employed underneath the specimen and no blankholder is needed, the operation is called two-point incremental forming (TPIF) [2, 3]. SPIF operation is studied in this research. For this type of sheet metal forming, the deformation not just occurred at the tool-sheet contact area but there is also some stretch at its vicinity [4]. Moreover, the necking criterion is not suitable for prediction of fracture and, instead, the fracture forming limit diagram (FFLD) should be employed [5].

One of important definitions in IF was proposed by Jeswiet et al. [1], where they selected the maximum possible wall angle in forming a frustum as the formability of the material. There are several parameters, such as sheet thickness, vertical pitch, spindle speed, feed rate, and tool diameter, affecting the formability. On the other hand, a multi-stage forming

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operation can also increase the formability [6]. Tool path is another parameter affecting the IF process. An appropriate tool path can provide a more homogeneous strain distribution [7]. In order to reduce the interfacial friction and improve the surface finish of the component, it is essential to employ a suitable lubricant. Finally, the geometry of the blankholder should have appropriate correlation and fitness with the final geometry of the specimen [8]. The surface roughness, depending on the application, can also be important for the final product. Process variables, such as tool diameter, vertical pitch, wall angle, feed rate, and the lubricant, considerably influence the surface roughness [1, 9]. The incremental forming process is not only used for metallic components but also is employed for forming polymeric sheets [10, 11].

Minutolo et al. [12] investigated the maximum wall angle attainable in IF of a frustum made of 1-mm-thick Al sheet. They numerically simulated the process and compared the finite-element and experimental results. However, it is difficult to carry out incremental forming of certain light alloys at room temperature, and doing the forming process at elevated temperature is unavoidable. By this remedy, the formability of the sheet can be increased. With this regard, Ambrogio et al. [13] conducted incremental forming of magnesium truncated cone at elevated temperatures. Their findings showed that at high temperatures, the formability increased considerably and, consequently, great cone wall angles were obtained. To provide a dynamic heating, laser beam were also involved in IF. Duflou et al. [14] employed a robot for IF of Al sheets. The movement of the forming tool was controlled by a 6-axis robot. On the other hand, a 3-axis laser generator simultaneously radiated a laser beam to the opposite side of the sheet component at the same point. It was shown that because of local heating, a better formability of the part was provided. Moreover, this dynamic heating mechanism resulted in less springback, compared with IF process of the same material at room temperature. However, this technique was too costly because it involved expensive equipment, such as a laser generator and a robot. Another hot incremental forming method required a dynamic electrical heating [15–17], where a DC power source with one pole attached to the blank and the other one connected to the tool was employed. At the tool-workpiece contact, a very high current density was created, and by this means, considerable heat was generated to locally warm up the component. This method was cheaper than the laser-heating technique, although the temperature control was more difficult. By changing the vertical pitch, tool diameter, and feed rate, one could alter the current passing though the contact area and, hereby, could control the amount of heat generated locally. Excessive current could result in sheet oxidation and low current density caused insufficient ductility for the material [15–17]. Ambrogio et al. [18] studied the hot incremental forming of aluminum, titanium, and magnesium sheets by using direct electrical current. The experimental results showed the best, intermediate, and worst deformation behaviors for these materials, respectively. Furthermore, because of an oxide layer at the tool-workpiece interface, the roughness of the surface of the product was considerably increased.

Efficient lubrication is one of the difficulties in IF at elevated temperatures. Oily lubricants cannot be employed at high temperatures because they react and produce toxic gases at elevated temperatures. On the other hand, it is hard to maintain a layer of solid lubricant at the tool-workpiece interface for an IF process because the lubricant is removed and displaced by the moving tool. To overcome these problems, Zhang et al. [19] introduced a new technique in which a porous layer of ceramic covered the sheet surface and then lubricated to maintain sufficient lubricant between the tool and sample.

Ji and Park [20] claimed that for warm IF of spherical shapes, it was better to deform the blank to an intermediate geometry, such as a cone, and then produce the final spherical shape in the second stage of the IF operation. Zhang et al. [21] studied the influence of the primary operation used for production of blanks on their deformation behaviors during the warm incremental forming process. They found that above a process temperature of 150 °C, there was less effect of anisotropic characteristics of the initial blank.

This investigation is concerned with the warm incremental forming of Ti-6Al-4V titanium sheets. With this regard, the influences of various parameters such as vertical pitch, tool diameter and sheet temperature on the forming limit diagrams, final temperature of the blank, drawing depth, springback, and thickness reduction of the sheet sample are studied.

2 Experimental procedures

2.1 The groove test

The groove test (GT) is a type of incremental forming in which a reciprocal tool path is defined such that a longitudinal groove is formed at the middle of a rectangle sheet. By applying a gradual vertical pitch to the tool, one can increase the depth of the groove until fracture occurs in the sheet. By this means, necessary data for drawing the forming limit diagram (FLD) are prepared. Because of the simple geometry of the specimen and very quick determination of a FLD, the groove test is a very good candidate for evaluation of formability of expensive materials such as titanium sheets. These advantages together with the simple tool paths involved have made the groove test an interesting experiment in IF investigations [22]. On the other hand, more experimental data could be extracted by means of the GT, which can be employed for estimation of temperature change due to in-process friction, determination of the thickness variation, and springback of the deformed sheet. However, since a different fracture criterion is employed in this test, the resulted FLDs are quite dissimilar to those obtained via traditional forming methods.

2.2 Design of blankholder and heater

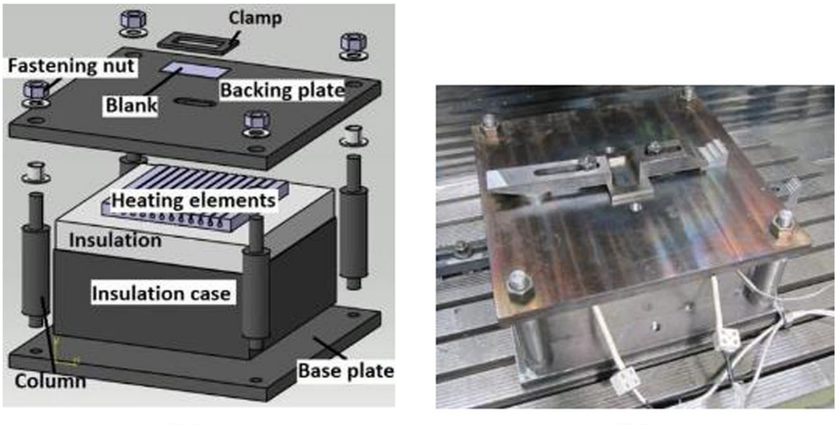
To perform a single-point incremental forming operation, the blank is usually fixed with a clamp during the forming process. On the other hand, to increase the formability of certain materials such as titanium sheets in several applications, heating the workpiece is necessary. For these reasons, a blankholder with a built-in electrical heater was designed and constructed for the present research work. Figure 1 shows the unassembled computer 3D model and the real picture of this setup. In order to carry out a GT, a groove should be machined in the backing plate to accommodate the incrementally deformed sample. To avoid probable tearing of the periphery of the specimen during the early stage of the process, an edge radius of 2 mm was machined around the edge of this groove on the backing plate [23]. In previous studies [13, 18, 24], the heat was generated in side walls of the setup and around the blank. This method resulted in a variable distribution of temperature in the workpiece. Therefore, the heating elements were mounted at the bottom of the isolated box (Fig. 1) and just under the workpiece. This remedy resulted in a much more uniform distribution of temperature in the blank. A PID controller system equipped with a thermostat and a thermocouple was used for controlling the temperature of the heater. Moreover, by providing an appropriate isolation, water-cooling system was eliminated from the experimental setup.

2.3 The material and test conditions

Ti-6Al-4V titanium sheets with the same thickness of 0.5 mm and 50 × 90 mm in-plane dimensions were used as the test samples. The vertical pitch should be selected very carefully. Large interval for this parameter might damage the tool and experimental setup and cause early fracture of the specimen. On the other hand, too close values for this variable could result in undistinguishable outcome for various experiments. Here, with some compromises, three vertical pitches were selected to be 0.1, 0.4, and 0.7 mm. Palumbo and Brandizzi [24] chose the process temperature between 200 and 400 °C. However, it should be kept in mind that to have certain strain hardening and to avoid recrystallization of the titanium alloy, the workpiece temperature should not exceed 650 °C. Considering to some extent the temperature rise due to the friction at the tool-sample interface, the heater temperatures for different incremental forming experiments were selected to be 100, 200, and 300 °C.

It is obvious that to reduce the interfacial friction, an appropriate lubricant should be employed. Because of elevated temperature of operation, many commercial lubricants should not be used. For the present research work, OKS 280, which was a type of grease containing graphite particles, was employed as a temperature-resistant lubricant [24].

To conduct incremental forming experiments, a tool with hemispherical head is needed. The diameter of this hemispherical head depends on the minimum edge and fillet radii of the specimen under consideration. Here, three different diameters of 8, 12, and 16 mm were chosen for this influencing parameter. The feed rate and spindle speed are the other two important variables in an IF process, affecting the formability of the sample. It is worthy to mention that, because of heat loss, the temperatures of the heater and the workpiece were not the same. Nevertheless, the heat generated by the interfacial friction could compensate this temperature difference. It is claimed [24] that for titanium alloys, a feed rate of 1800 mm/min and a spindle speed of 400 rpm resulted in a temperature rise of 100 °C in the workpiece. Increasing the spin speed to 1600 rpm with the same feed rate, the sample temperature increased to about 180 °C. To avoid significant temperature change due to friction, the feed rate and spindle speed were respectively selected to be 400 mm/min and



(a) (b)

Fig. 1 The experimental setup for warm incremental forming of titanium sheets. **a** The unassembled computer model. **b** The assembled actual setup

400 rpm for the present investigation. Under these conditions, not only the interfacial heat generation was quite controlled but also data recording during the experiment was performed more easily.

It is illustrated [25] that the anisotropy of the sample had a minor influence on its formability via an IF operation, especially at the elevated temperatures. For this reason, the anisotropy of the metal sheet is not considered here. It was also shown [7] that a spiral tool path provided a much better strain distribution in the workpiece. This type of path is also chosen for this research work. In other words, the vertical pitch is gradually applied along the length of the tool path.

For a better observation of the sheet stretch and a more accurate determination of the major and minor strains, the periphery of the sample was completely fixed to avoid its slip between the blankholder and the backing plate. To measure the major and minor strains, the sheet sample was first cut into suitable designed dimensions. Afterwards, it was pickled for printing a network of circles on its underneath (not in contact with the tool) surface. The network of circles was designed to employ circles as small as possible in order to evaluate as accurate as possible the local strains. One of advantages of this network, compared with the previous ones, was that each circle of the network was surrounded with six identical circles having the same distances from each other and the central circle. Moreover, to avoid any thermal stress and/or stress and strain concentrations, the circles were not etched or engraved on the blank surface. Instead, the designed pattern of circles was printed on the underneath surface of the blank such that it remained after incremental deformations at elevated temperatures. Figure 2 illustrates the designed network of circles together with a typical titanium sheet painted with this pattern.

2.4 Method of experiment

To observe the mechanical behavior of Ti-6Al-4V sheet at elevated temperatures, several tensile tests were conducted. The test samples were prepared based on ASTM E8 [26] standard. Figure 3 shows the experimental results. The ram speed was 2 mm/min resulting in an engineering strain rate of 6.5×10^{-4} s^{-1}. The tensile tests were performed at various temperatures, namely between 200 and 700 °C. Going through Fig. 3, one can observe that the higher the temperature, the higher is the fracture strain and the lower is the flow stress of the material. For instance, the ultimate strength at 600 °C is about half of that at 200 °C, whereas the ductility at the former temperature is about 2.5 times that of the latter one.

In conducting the IF experiments, it was found that the temperatures of the heater and the sheet sample were not the same. This was due to the heat transfer between the specimen and the surroundings. For this reason, for each value of heater temperature, the temperature of the sheet sample just located over the heater was measured using a Mikron pyrometer. Figure 4 demonstrates the temperature of the sample as a function of heater temperature. Using this graph, one can estimate the sheet temperature based on the temperature set-point of the electrical heater.

As mentioned previously, a spiral tool path can provide a more homogeneous deformation in an IF operation. For this reason, this type of tool path was adopted for conducting the IF experiments. For each test, the incremental deformation of the specimen was continued until the formation of a crack in the sheet sample. Meanwhile, the temperature of the deformation zone was measured and recorded simultaneously by means of a pyrometer.

3 Results and discussion

Figure 5 illustrates the initial and final temperatures of the sample for various groove tests. The final temperature was measured just when a crack occurred in the sheet sample. It is obvious that there is a significant difference between these temperatures, owing to the high interfacial friction, lack of enough time for heat transfer from the sheet, and the slight decrease in distance between the workpiece and the heating elements due to formation of the groove. For a better review of the experimental findings, a specific code was used for each test, showing (from left) the values of heater temperature, tool diameter, and vertical pitch. For instance, code 300-16-0.7 illustrates that for the groove test, the heater temperature was 300 °C, the tool diameter was 16 mm, and, finally, the vertical

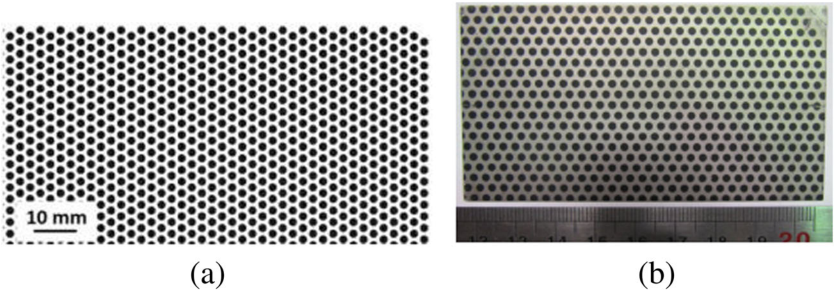
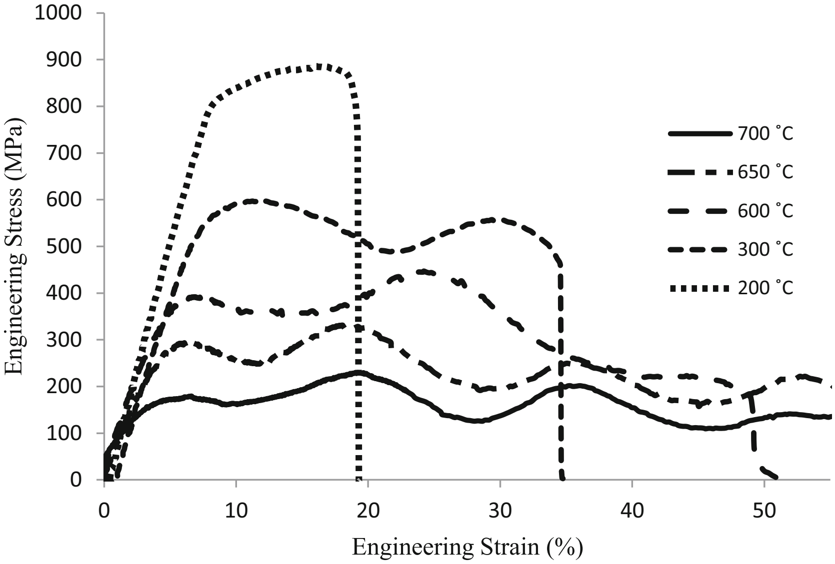


Fig. 2 **a** The final network of circles designed for determination of the major and minor strains. **b** The pattern printed on a typical sample

Fig. 3 The engineering stress-strain curves of Ti-6Al-4V at various temperatures and for a constant tension rate of 2 mm/min



pitch was 0.7 mm. As was expected, the greater the heater temperature, the higher was the final temperature of the sheet sample. However, as mentioned above and as can be seen in Fig. 5, there was a notable difference between these temperatures. This was mainly due to high interfacial friction between the tool and workpiece during the GT, especially when the lubricant had been removed after a few rounds of the tool path. During an IF operation and when the tool is engaged with the sheet, there is no sufficient time for heat transfer from the deformation zone. Consequently, the sample temperature increases significantly, compared with its initial value.

The high difference between the initial and final temperatures of the specimen is an undeniable fact because it happened for all the 27 groove tests. In metal forming operations, the heat is generated either by plastic deformation or by interfacial friction. In an IF process, the heat due to permanent deformation of the material is not major, although some variables such as the vertical pitch and feed rate can increase this type of heat generation. However, the friction at the tool-sample interface is the actual and main source of heat generation because the relative speed due to the fast rotation of the spindle is very high. This sort of temperature rise can be intensified when the lubricant failed and/or the engaged areas of the tool head and the workpiece increase, for instance when the groove is formed and the tool head penetrates the sheet or the tool diameter is increased.

Based on Fig. 5, one can find out that the larger the tool diameter, the greater is the amount of heat generation and temperature rise. This is in agreement with observations made by Palumbo and Brandizzi [24] and is mainly due to a larger tool-workpiece contact area for bigger tools. The vertical pitch has also the same influence on the sheet temperature. When this parameter is increased, larger strains are induced into the sample

Fig. 4 Variation of actual sheet temperature with the set-point temperature of the heater

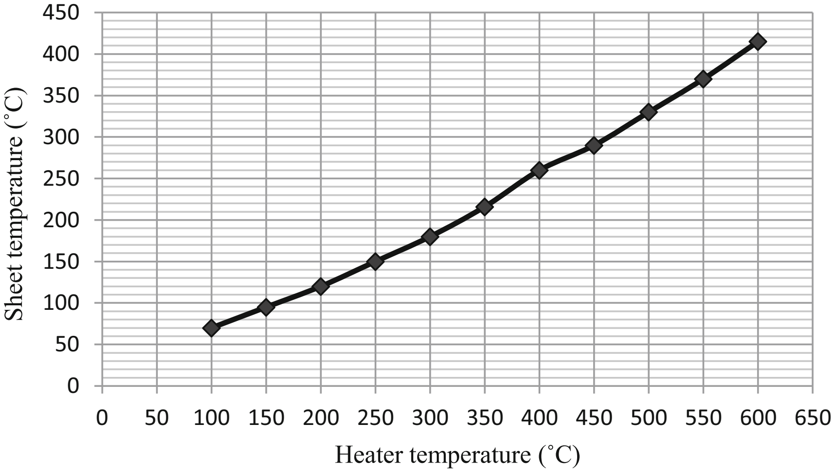
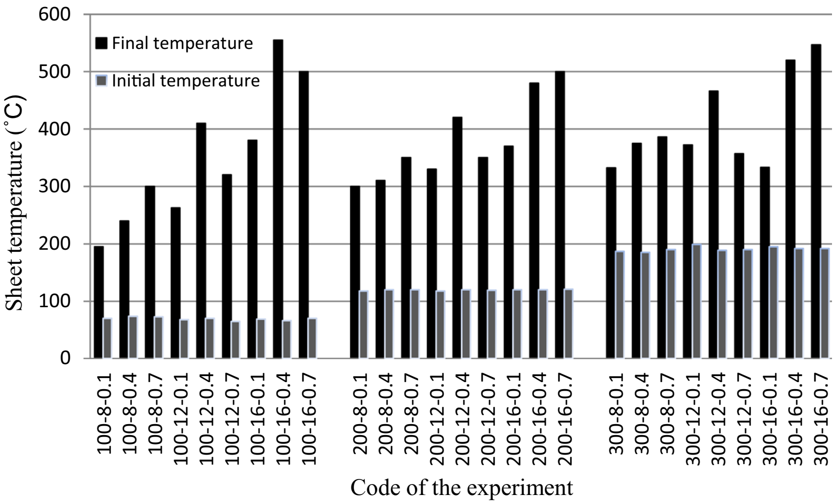


Fig. 5 The initial and final temperatures of the sheet sample for different IF tests



during each path of the process and the specimen represents a higher resistance to thinning. Therefore, the interfacial contact pressure and, consequently, the friction at the tool-workpiece interface increase, and this situation generally results in a greater temperature rise for the deformed sheet. Nevertheless, the effect of the vertical pitch is not the same for various tool diameters. When the tool diameter is 8 mm, any increase in the vertical pitch can cause a more significant increase in the sample temperature. However, for larger tools (12 and 16 mm tool diameters), when the vertical pitch is increased, after a fewer rounds of the tool path the specimen is fractured and the test is stopped. For this reason, in a few cases the temperature rise for larger vertical pitches is quite lower than that of a smaller value of this variable.

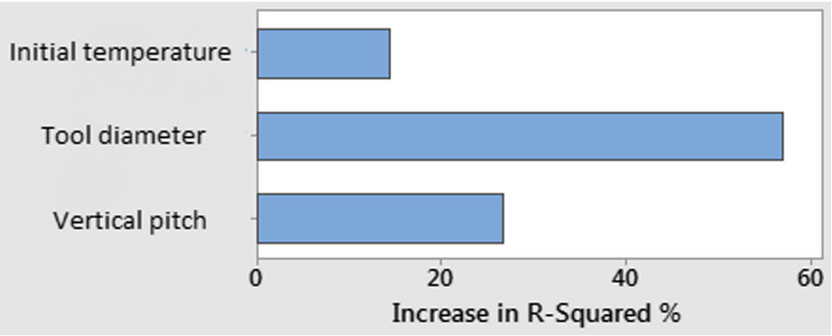
Using the experimental data gained in this research and the multiple regression facility of Minitab software, the following equation was found for the final temperature of the sheet:

$$T_f = -150.5 + 1.323\,T_i + 28.69\,D_t + 423\,P_v - 604\,P_v^2 - 0.0819\,T_iD_t + 17.71\,D_tP_v \quad (1)$$

where T_f (°C), T_i (°C), D_t (mm), and P_v (mm) are respectively the final temperature, initial temperature, tool diameter, and the vertical pitch. R^2 for this multi-variable regression model was found to be about 89 %. Figure 6, which is one of the software outputs, illustrates how the process parameters influence the fitness of the above relation on the experimental findings. With this regard, the most contribution is attributed to the tool diameter (D_t). The changes of the final temperature with individual variations of the three process variables are also shown in Fig. 7. It is clear from this figure that despite the initial temperature and the tool diameter, there is a nonlinear effect of the vertical pitch on the final temperature of the sheet.

The groove formed at the centerline of the sheet sample can be divided into three regions, two axisymmetric regions at the ends and one longitudinal at the middle. In the end regions of the groove, there is a 3D state of stress, whereas in the longitudinal middle part, the deformation can be assumed to be plane strain. It is worthy to mention that the fracture, in most of the cases, occurred at the end regions of the groove. When a crack initiated in the specimen, the position of the tool head was measured with respect to the initial reference point.

Fig. 6 The incremental impacts of the process variables on estimation of the final temperature of the titanium sheet



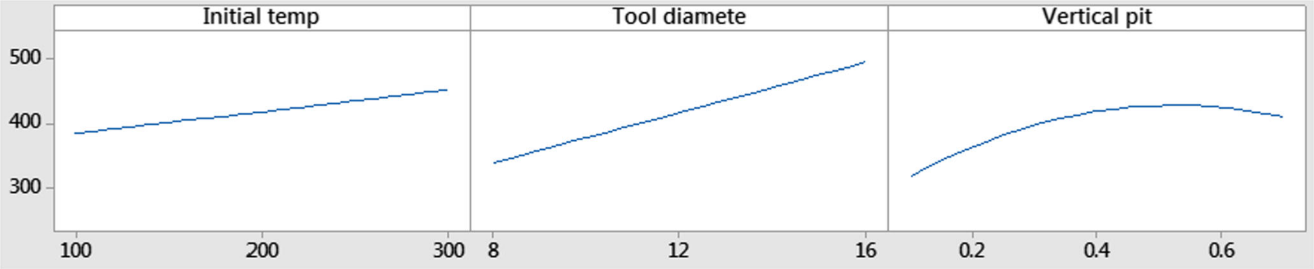


Fig. 7 Variations of the final temperature with the individual changes of the process variables

This value was considered as the drawing depth for the relevant groove test. The influences of the forming variables on the drawing depth are shown in Fig. 8. It can be seen in this figure that the greater the heater temperature, and consequently the sheet temperature, the greater was the drawing depth. This was mainly due to better ductility and formability of the alloy at higher temperatures. Previous studies [1] have illustrated that for a cold IF operation, the formability of the sheet was reduced by an increase in tool diameter. This could be caused by considerable heat transfer from the specimen during the operation which, in turn, reduced the strain localization and temperature rise in the sheet sample [1]. However, there was a reverse situation in the present research work, where with any increase in the tool diameter, the interfacial friction and, consequently, the sheet temperature increased and, finally, the drawing depth enlarged due to ductility enhancement of the alloy.

Going through Fig. 8, one can find out that a growth in the vertical pitch resulted in a greater drawing depth. This observation is in contrast with that of cold IF processes, where by applying a larger deformation without any temperature rise in the sample, the formability of the sheet decreases with the increase in vertical pitch [1]. Nevertheless, the experimental findings for vertical pitches of 0.4 and 0.7 mm are very close to each other. This can be explained by two opposite effects of this pitch growth. For this increase in the vertical pitch, on one hand, there was a greater temperature rise in the sample and, on the other hand, larger strains were induced and, subsequently, a greater resistance to thinning existed. These opposite influences compensated each other and, finally, caused quite similar results for 0.4 and 0.7 mm vertical pitches.

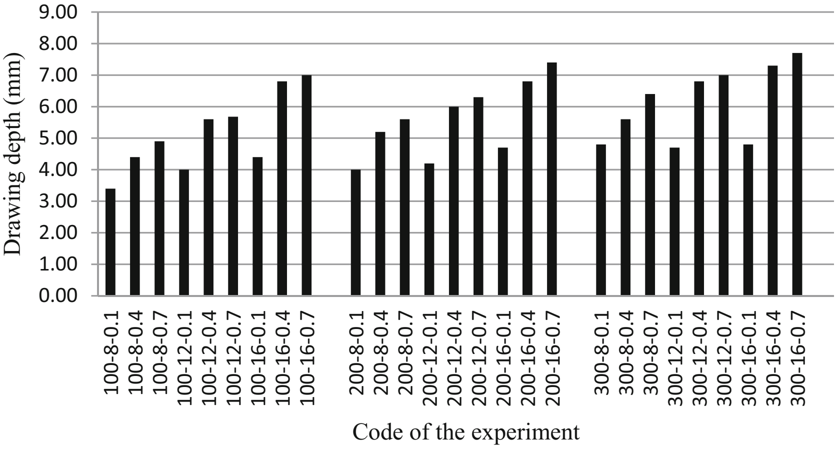
After conducting a multi-variable regression analysis, the following formula was obtained for prediction of the drawing depth (D_d) in millimeters:

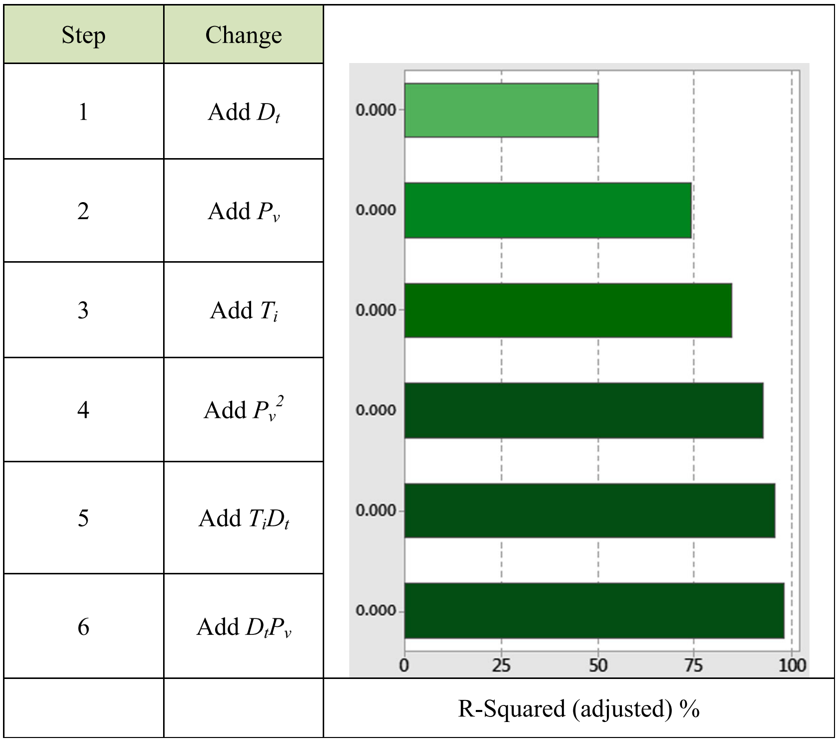
$$\begin{aligned} D_d = & -0.063 + 0.01323\, T_i + 0.2003\, D_t \\ & + 7.187\, P_v - 8.237\, P_v^2 - 0.000659\, T_i D_t \\ & + 0.2431\, D_t P_v \end{aligned} \tag{2}$$

For this estimating relationship, the R^2 is more than 98 % which is significantly greater than that of the final temperature. Figure 9 illustrates how the complimentary terms added during various steps of the regression analysis contributed to achieving such an excellent fitness. Based on the outputs of the Minitab software, the greatest impact in improving the R^2 belongs to terms involving the vertical pitch. Moreover, variation of the drawing depth with the vertical pitch is nonlinear, whereas with the initial temperature and tool diameter, it is linear.

After performing the groove test, each circle of the printed pattern deformed into an ellipse. Having the

Fig. 8 The effects of the test variables on the drawing depth for the warm incremental forming of titanium sheets



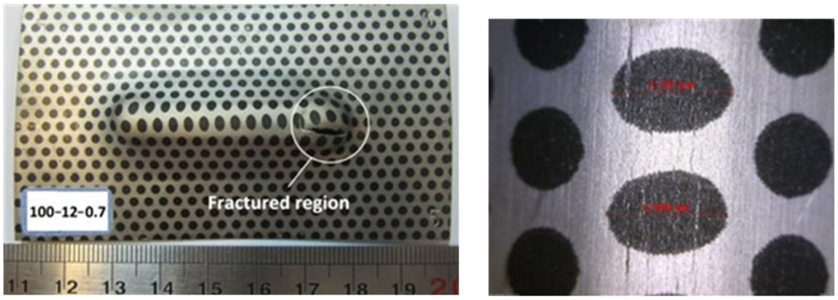


Step	Change
1	Add D_t
2	Add P_v
3	Add T_i
4	Add P_v^2
5	Add T_iD_t
6	Add D_tP_v

Fig. 9 The order in which the terms are added to improve the prediction of the drawing depth by Eq. (2)

diameter of the original circle and measuring the major and minor diameters of the ellipse, one could calculate the major and minor strains for a specific position of the deformed sample. Since the circles were very small, to increase the accuracy of measurements, a Dino digital microscope was employed to measure the major and minor diameters of each ellipse (Fig. 10). It is worthy to mention that what were initially measured were the chords of the curved diameters of an ellipse. Hence, necessary modifications were performed based on the curvatures of the tool head and the deformed sheet. Indeed, despite the previous investigations, the actual diameters of the flattened ellipse were determined for calculation of the major and minor strains for different points of the grooved specimen. Using this technique and after calculation of various strains, the forming limit diagram was obtained for different process temperatures. Figures 11, 12, and 13 show the FLDs for 100, 200, and 300 °C. It is notable that these forming limit diagrams were prepared for the plane-strain middle part of the grooved sample.

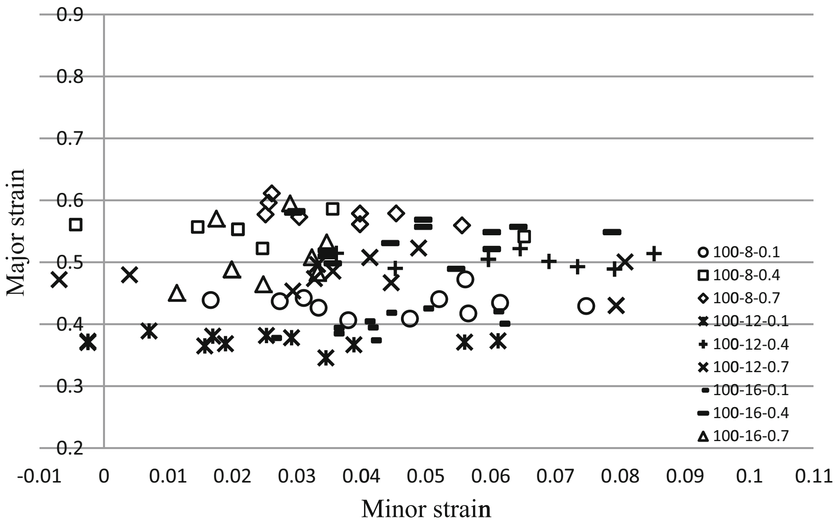
The minor strains, which are along the sample groove, are considerably smaller than the major ones. Therefore, the value of the major strains can be considered as a measure of drawability of the sheet. Hence, the higher the locations of the sampling points in a FLD, the higher is the formability of the alloy. For specified process temperature and tool diameter, the greater the vertical pitch, the larger is the drawability of the sheet. The temperature rise during the process is the main reason for this phenomenon. Nevertheless, the results for 0.4 and 0.7 mm pitches are quite close to each other. In this case, the greater thinning resistance due to larger imposed strains nearly compensated the softening of the material due to the temperature increase, although the temperature influence



(a) (b)

Fig. 10 **a** A typical specimen fractured at the end of a groove test. **b** The image of the deformed circular pattern under the optical microscope for measurement of the major and minor strains

Fig. 11 The FLDs for various groove tests conducted at a heater temperature of 100 °C

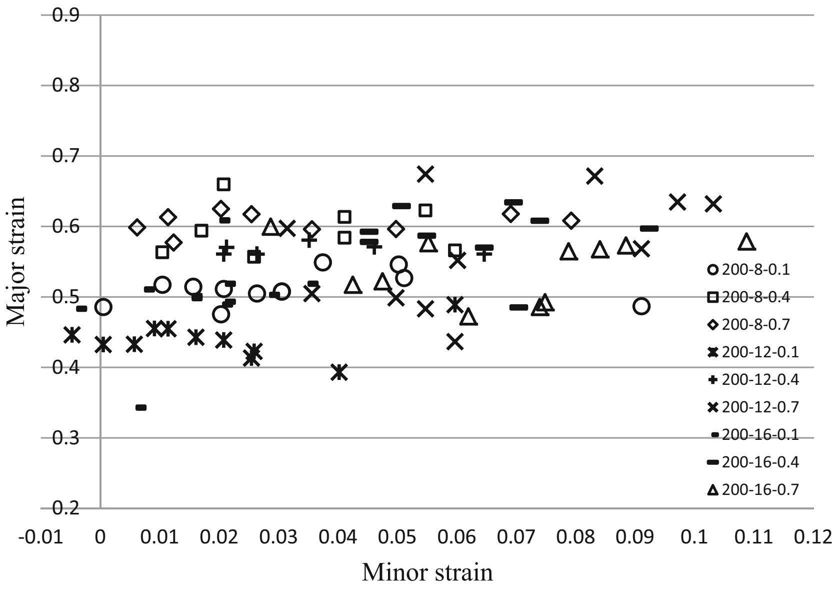


has the upper hand and, finally, the drawability was increased for the larger vertical pitch.

Keeping all the parameters excepting the tool diameter unchanged, one may imagine that, because of less stress and strain concentrations, the deformation of the sample should be lower for bigger tools [1]. However, in the present investigation, due to a significant effect of the temperature rise during the operation, no specific trend was observed for the influence of the tool diameter. Similar to the previous research work [13], any increase in the initial temperature of the specimen resulted in greater formability for the sample (Figs. 11, 12, and 13).

To study the springback in the present investigation, several deformed parts were selected to examine the effects of the tool diameter, vertical pitch, and temperature. These components were three-dimensionally scanned using an ATOS optical measuring device. The 3D images were transversely cut in the CATIA software in order to obtain the transverse profiles of the deformed sheet samples. Afterwards, considering the final depth of the deformed specimen, the desired target profile was overlaid on the abovementioned actual transverse profile. By comparing these two profiles (Fig. 14), it was possible to study the effects of various process variables on the springback of the incrementally deformed sheet. The elastic recovery of the sample was mainly due to passing the tool away from a localized deformation zone and removing the final grooved sheet from the clamp of the experimental setup [1]. As a measure of the springback, the angular difference (θ_1–θ_2) between the target and actually deformed flanges of the component

Fig. 12 The effects of different parameters on the FLD of Ti-6Al-4V incrementally deformed with a heater temperature of 200 °C



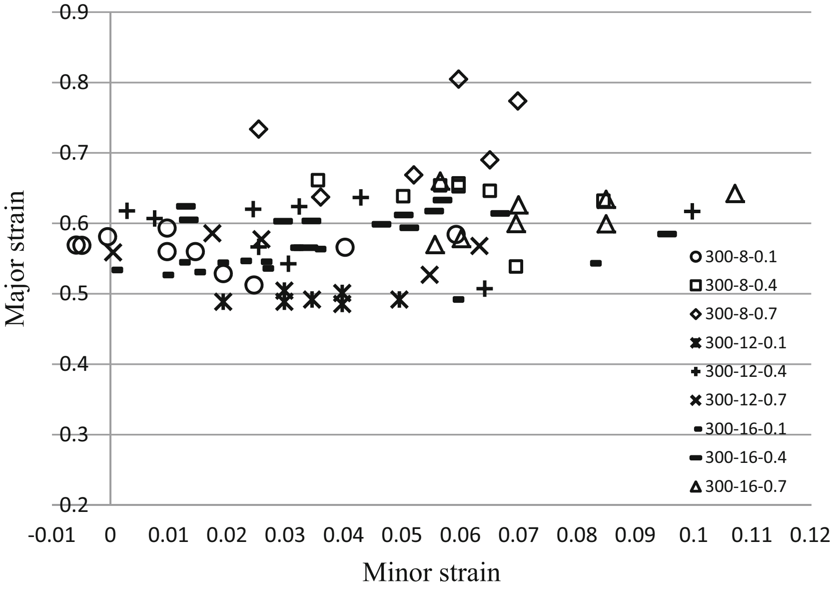


Fig. 13 The forming limit diagrams of the alloy under consideration for the groove tests with a heater temperature of 300 °C

was calculated (see Fig. 14). A larger value of this angular difference means a greater springback of the sample. The calculated angles and their differences for various specimens are summarized in Table 1.

Going through these experimental results, one can find out that the process temperature (either the initial or the final temperature) plays an important role in incremental forming of the titanium sheet. The springback of the deformed part is mainly influenced by the elastic modulus, the level of the flow stress, and the distribution of the residual stresses in the grooved sheet. The temperature of the specimen affects all these variables, but not in the same way. For instance, by increasing the sheet temperature, both the elastic modulus and flow stress of the material are reduced (see Fig. 3). However, reduction in the Young's modulus increases the springback, whereas reduction in the flow stress decreases the amount of elastic recovery. The higher the sheet temperature and the larger the tool diameter, the greater was the final temperature and the lower was the springback of the component. In other words, the flow stress reduction overwhelmed the Young's modulus decrease. A larger vertical pitch also imposed larger strains into the component and, as can be seen in Table 1, this has increased the springback of the final product. It is worth mentioning that when the initial and final temperatures of the specimen increase, the formability and drawing depth of the sample also increase, and this could also affect the residual-stress distribution and the amount of springback.

The variation of thickness of the deformed component is another important subject in investigating the IF process. For this purpose, the grooved sheet was transversely cut by means of wire cutting. Afterwards, the variation of thickness in the transverse direction and

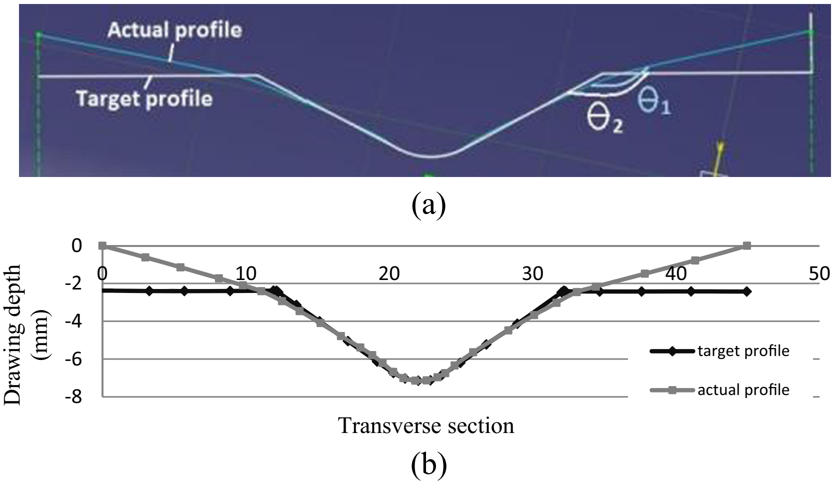


Fig. 14 **a** Overlaid target and actual profiles for test 300-8-0.1 in CATIA software. **b** The springback of the sheet sample, based on the same drawing depths for both the profiles

Table 1 The target and actual angles together with their difference, as a measure of springback, for several groove tests

Process variable effects	Experiment code	Target angle	Actual angle	Angular difference	Experiment code	Target angle	Actual angle	Angular difference
Vertical pitch	100-8-0.1	173.7	159.6	14.1	300-8-0.1	169.1	151.7	15.5
	100-8-0.7	172.5	151.3	21.2	300-8-0.7	163.8	147.6	16.2
Tool diameter	100-8-0.7	172.5	151.3	21.2	300-8-0.7	163.8	147.6	16.2
	100-16-0.7	150.5	133.2	17.3	300-16-0.7	150.0	128.6	12.7
Temperature	100-8-0.7	172.5	151.3	21.2	100-16-0.7	150.5	133.2	17.3
	300-8-0.7	163.8	147.6	16.2	300-16-0.7	150.0	128.6	12.7

in the vicinity of crack location was determined using three different methods, namely by a micrometer, by 3D scanning of the cut workpiece, and by using a profile projector device. By employing these techniques for the flange (undeformed part) of the sample, it was found that the last method, i.e., measuring with the profile projection, resulted in the most accurate findings for the thickness of the sheet. For a typical component, the measured variation of thickness in AutoCAD software is plotted in Fig. 15. For the same experiments employed for studying the springback, the least thickness of the final product and the maximum thickness reduction were determined and summarized in Table 2. Based on these experimental findings, one can observe that the greater the vertical pitch, the larger is the thickness reduction, and this is the case for both the process temperatures. For a larger vertical pitch, there was a greater heat generation and actual process temperature (see Fig. 5). This caused a sheet softening and, based on the corresponding FLDs (Figs. 11 and 13), a greater drawability for the titanium sheet. Keeping in mind the volume constancy of plastic deformations, one can conclude that there should be a greater reduction in thickness for a more stretched sample. Therefore, it is reasonable to have a thinner product when the vertical pitch is increased.

For both the 100 and 300 °C temperatures, it can be seen in Table 2 that the thickness decrease is smaller for the bigger tools. Although the actual temperature for a thicker tool is more or less higher, since the deformation is distributed in a larger zone of the sample and the stretch of the sheet is smaller, the thinning of the workpiece is generally smaller, compared with a small tool with a more localized plastic deformation. In other words, when the tool diameter is increased, because of lower strain concentration, the sheet stretch is reduced. Finally, it is obvious that for a higher initial and/or final process temperature, the ductility and drawing depth of the workpiece are greater and, consequently, a larger reduction in the sheet thickness should be observed. This is what the last couple or rows in Table 2 illustrate.

Figure 16 shows the microstructures of the initial and incrementally deformed titanium alloy (experiment 300-8-0.1). A MIC 10420 image analyzer was employed to obtain these micrographs. Comparing these microstructures, one can find out that, because of plastic strains induced during the process, the grains of the deformed part are more elongated and quite smaller than those of the as-received alloy. Using the linear intercept method, the average grain sizes of the undeformed and final components were found to be 6.8 and 5.9 μm, respectively.

4 Conclusions

In this article, various warm groove tests were performed with Ti-6Al-4V titanium sheets in order to study the influences of different parameters, such as the initial temperature, vertical pitch, and tool diameter on the process outcomes, including the final temperature, drawing depth, forming limit diagram, springback, and the variation of thickness of incrementally deformed products. Based on the research work conducted and the

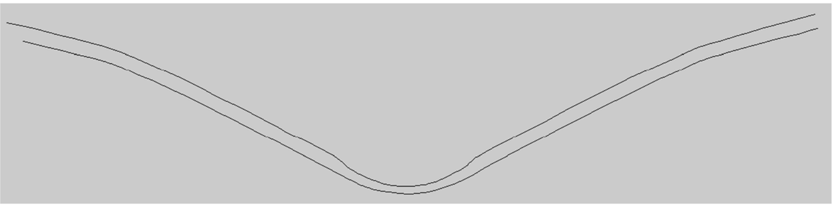


Fig. 15 The variation of the sheet thickness incrementally deformed via test 300-8-0.1, at the vicinity of fracture location

Table 2 The minimum thickness and the relevant maximum thickness reduction for selected incrementally grooved titanium sheets

Process variable effects	Experiment code	Least thickness (mm)	Thickness reduction (mm)	Experiment code	Least thickness (mm)	Thickness reduction (mm)
Vertical pitch	100-8-0.1	0.340	0.160	300-8-0.1	0.275	0.225
	100-8-0.7	0.335	0.165	300-8-0.7	0.260	0.240
Tool diameter	100-8-0.7	0.335	0.165	300-8-0.7	0.260	0.240
	100-16-0.7	0.362	0.138	300-16-0.7	0.356	0.144
Temperature	100-8-0.7	0.335	0.165	100-16-0.7	0.362	0.138
	300-8-0.7	0.260	0.240	300-16-0.7	0.356	0.144

experimental findings obtained, the following conclusions could be drawn:

1. The groove test (GT) is a benchmark test and, according to several researchers, its results are beneficial for incremental forming (IF) operation, although some researchers preferred to try other types of the IF process such as incremental forming of a frustum. This comprehensive research, involving 27 different warm groove tests, has qualitatively and quantitatively shown the sensitivity of the GT to some important process variables for warm IF of an expensive material, namely Ti-6Al-4V titanium. Selection of the groove test for the present investigation has significantly reduced the required costs and struggles because it is relatively simple to do and requires low amounts of material and time.
2. There is a significant difference between the measured initial and actual temperatures of the sheet sample, and the heat generated during the operation has definitely affected the formability of the material. With this regard, the interfacial friction plays an important role in warm incremental forming of titanium alloy because it can produce a large amount of heat and locally increase the sheet temperature. This significant temperature rise complicatedly affects the material properties and the distribution of the residual stresses in the final product.
3. Compared with the previous investigations, the heating method employed here provided a considerably more homogeneous temperature distribution in the workpiece. Furthermore, some innovations were utilized for measuring the principal strains, such as a more appropriate and sustainable network of circles without any strain concentration, considering the curvature of the sheet and using a digital microscope for calculation of strains.
4. The greater the sample temperature and the larger the tool diameter, the higher is the final temperature and the lower is the springback of the product. The reason for decrease of springback is that the flow stress reduction overcomes the Young's modulus diminution when the temperature rise occurs during the IF of titanium sheets. On the other hand, the greater the vertical pitch, the larger are generally the formability, drawing depth, and the springback of the sheet sample.
5. Based on the regression analyses carried out and the predictive relations obtained, the vertical pitch possesses nonlinear effects on both the final temperature and drawing depth. Moreover, it has the greatest contribution in improving the R^2 for the drawing depth relationship. However, in prediction of the final temperature (Eq. (1)), the tool diameter plays such a role.
6. The experimental findings of the present investigation are more applicable for small-size titanium parts (i.e., with sizes around the dimensions of the specimens of this research work). The heat generation, lack of time for sufficient heat transfer, and the temperature rise of the sheet sample are more serious for this type of components compared with large sheet products.

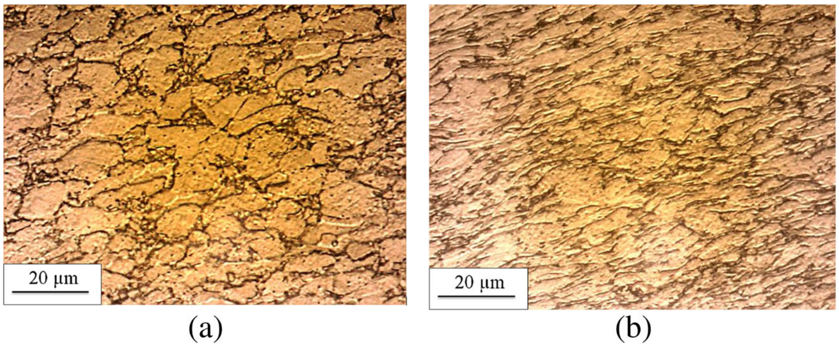


Fig. 16 **a** Microstructure of the as-received titanium alloy. **b** The micrograph of the sample grooved by means of a typical IF test

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