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# On the Surface Quality of Incrementally Formed Niobium Sheets

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**Abstract.** Incremental sheet forming is a viable method for manufacturing highly customized components from non-conventional materials. Among these, niobium is a metal of growing interest due to its potential in various technological applications. In this experimental study, the incremental forming of high-purity annealed niobium sheets was investigated, with particular attention given to the surface finish of the formed parts. To this end, the surface morphology of the components, specifically fixed wall conical frusta, and the forming forces were analyzed. The results indicate that, despite the material's notable formability, the incrementally formed niobium surfaces exhibit poor quality. This is attributed to the unique properties of niobium, suggesting that the development of surface treatment strategies is advisable to improve this aspect.

## Introduction

Niobium (Nb) is a ductile transition metal that exhibits several distinctive properties, making it suitable for a wide range of technological applications. One of the most demanding and compelling uses is in the fabrication of superconducting radiofrequency (SCRF) accelerating cavities [1] because among superconducting materials, Nb exhibits the highest lower critical magnetic field and superconducting transition temperature and a high normal state thermal conductivity [2-4].

However, this non-conventional material is subject to complex and unusual surface phenomena that can compromise the quality of the finished surfaces (an aspect of primary importance for SCRF cavities in service [5]). For instance, predicting the surface finish after a metal forming process can be challenging [6], and the resulting surfaces may exhibit an orange peel effect and high roughness due to the non-uniform deformation of large grains with varying crystalline orientations [7]. Moreover, the sheets may be affected by galling, a type of adhesive wear characterized by the macroscopic transfer of material between metal surfaces due to their relative sliding motion [8].

Incremental sheet forming is a manufacturing technique originally developed for common metal alloys as an alternative to conventional forming methods, particularly for shaping flat metal sheets into complex three-dimensional profiles [9]. The core principle of this technique involves the progressive deformation of a clamped sheet of material by a forming tool, which is controlled by a computerized numerical control (CNC) machine. The tool follows a programmed path, gradually shaping the sheet into its final geometry [10]. More recently, this process has been applied to metals that are traditionally difficult to form, such as magnesium, titanium, and their alloys [11-13], with the goal of improving both formability and surface quality.

A previous study by the authors [14] examined key aspects of the incremental forming of thin rolled Nb sheets, including formability limits, forming forces, surface roughness, and other relevant parameters. The study revealed that, despite the brittle nature of the material, the sheets exhibited remarkably high formability during incremental forming. A maximum formability angle of approximately 75° was achieved through varying wall angle conical frusta tests. Furthermore, fixed wall angle tests resulted in very low surface roughness values under different tool/sheet contact conditions, although scratches caused by galling were still observed.

This work presents an experimental investigation into cold incremental forming of high-purity annealed RRR300 Nb sheets. By analyzing the forming forces and the morphology of the worked surface, the study aims to correlate the surface quality of incrementally formed Nb components with their mechanical properties, while proposing strategies to enhance the understanding of incremental forming applied to Nb sheets.

## Materials and Methods

Fixed wall angle conical frusta were fabricated using cold incremental sheet forming, starting from high-purity annealed RRR300 Nb sheets (supplied by Ningxia Orient Tantalum Industry Co., LTD) with a thickness of 1.0 mm. The main geometrical features of the conical frusta are listed below (see Fig. 1):

- wall angle $\alpha = 60°$;
- height $h = 35$ mm;
- radius of the major base $R = 35$ mm.

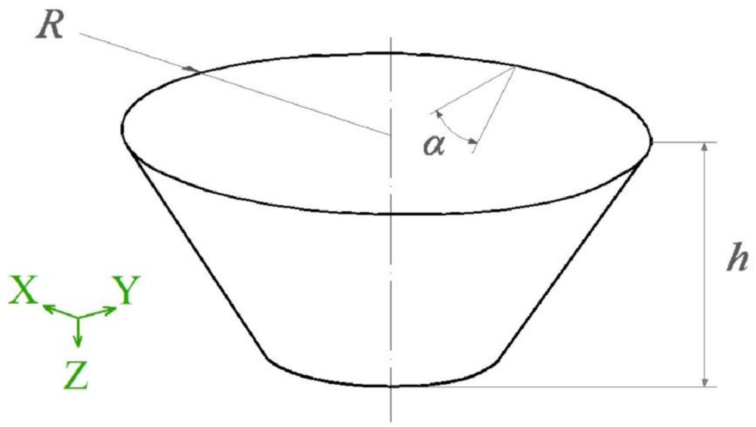


**Fig.1.** Geometrical features of the conical frusta

A C.B. Ferrari high-speed four-axis vertical machining center operated at a feed rate of 1000 mm/min, driving a non-rotating stainless-steel stylus with a hemispherical head, 10 mm in diameter. The stylus acted as the forming tool for the sheet, which was clamped along its periphery by a blocking system with a square area measuring 100 mm per side. These process parameters have been chosen by considering both the available literature and previous papers of the authors where the incremental forming of niobium sheets has been investigated.

A unidirectional spiral-based strategy was adopted as the toolpath, with a vertical step depth of 1 mm. Furthermore, the process was carried out under lubricated conditions using Boelube 70104 (100A) lubricant (supplied by Orelube) to minimize the risk of failure and defects [15].

An image of the experimental setup is shown in Fig. 2.

The formed parts were inspected for failures and/or defects, including twisting, which was quantified by measuring the twist angle (it corresponds to the rotation angle after the forming process of a cross, marked on the bottom of the plane sheets, with respect to its initial position), to assess the formability of the incrementally formed Nb sheets.

Additional insights were obtained through the evaluation and interpretation of the forming forces ($F_{XY}$, $F_Z$ and $F_{TOT}$, representing the in-plane, vertical and total forming forces, respectively) as well as the moment around the vertical axis ($M_Z$). These parameters were recorded at a sampling rate of 50 Hz using a K-MCS10 multicomponent sensor, integrated with the QuantumX MX840B data acquisition system and Catman Easy AP software.

Finally, the surface quality was assessed through visual inspection and roughness measurements (five repetitions) taken along the cross-section of the formed surfaces using a Mitutoyo Surftest SJ-301 tester. The evaluation adopted differential inductance and Gaussian filters as the detecting method, with the cut-off value selected in accordance with ISO 4288-1996 standards.

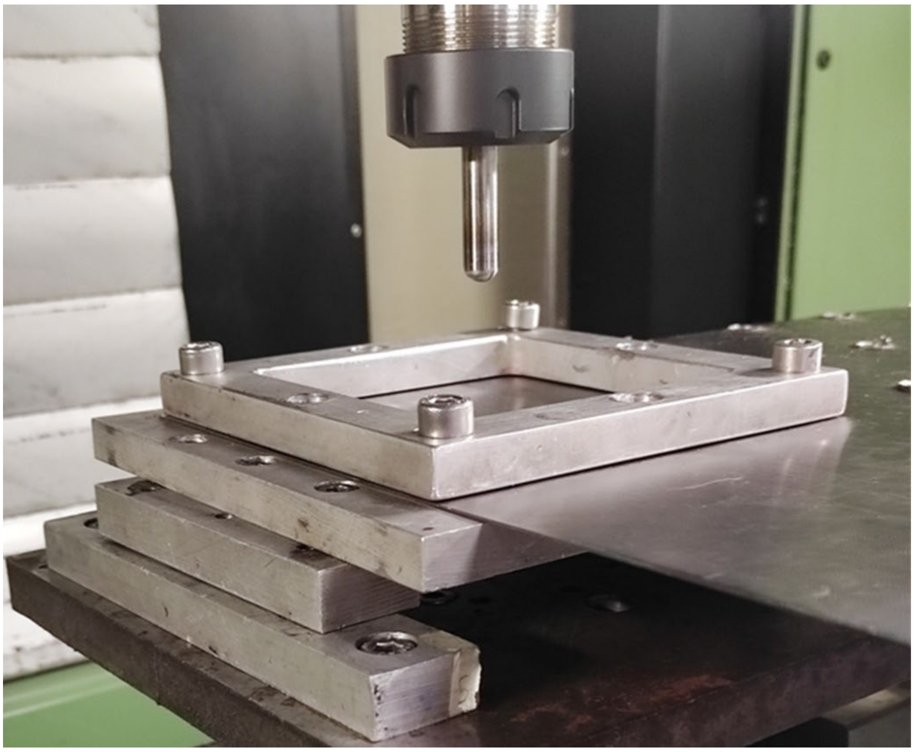

**Fig. 2.** Experimental setup of the incremental sheet forming process

**Results and Discussion**

The process was carried out successfully (Fig. 3 shows a conical frustum), without any tearing or wrinkling. However, the frustum exhibited a twisting angle of 2.4°, which is attributed to in-plane forming forces generating a torque (*Mz*). Compared to incrementally formed polycarbonate sheets under similar working conditions [16], where this phenomenon also led to instabilities, the observed twisting was minimal.

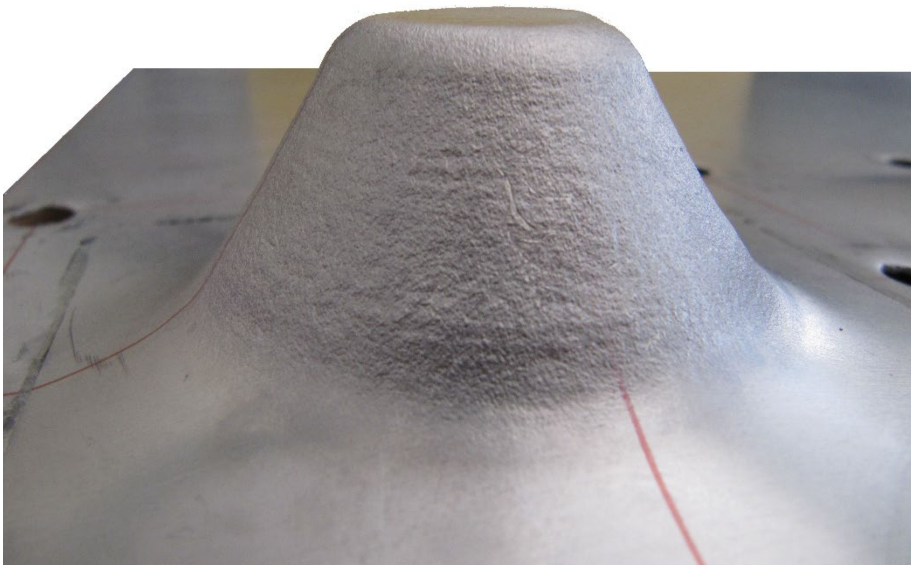

**Fig. 3.** Conical frustum produced via incremental sheet forming

Fig. 4 shows the trends of the forming forces and the moment $M_Z$. After an initial transition phase, the forces (Fig. 4a) reached a quasi-steady state condition, corresponding to the plastic deformation of the sheet. This condition was associated with a decrease in $M_Z$ (Fig. 4b), due to the progressive reduction in the diameter of the conical frusta as vertical displacement increased.

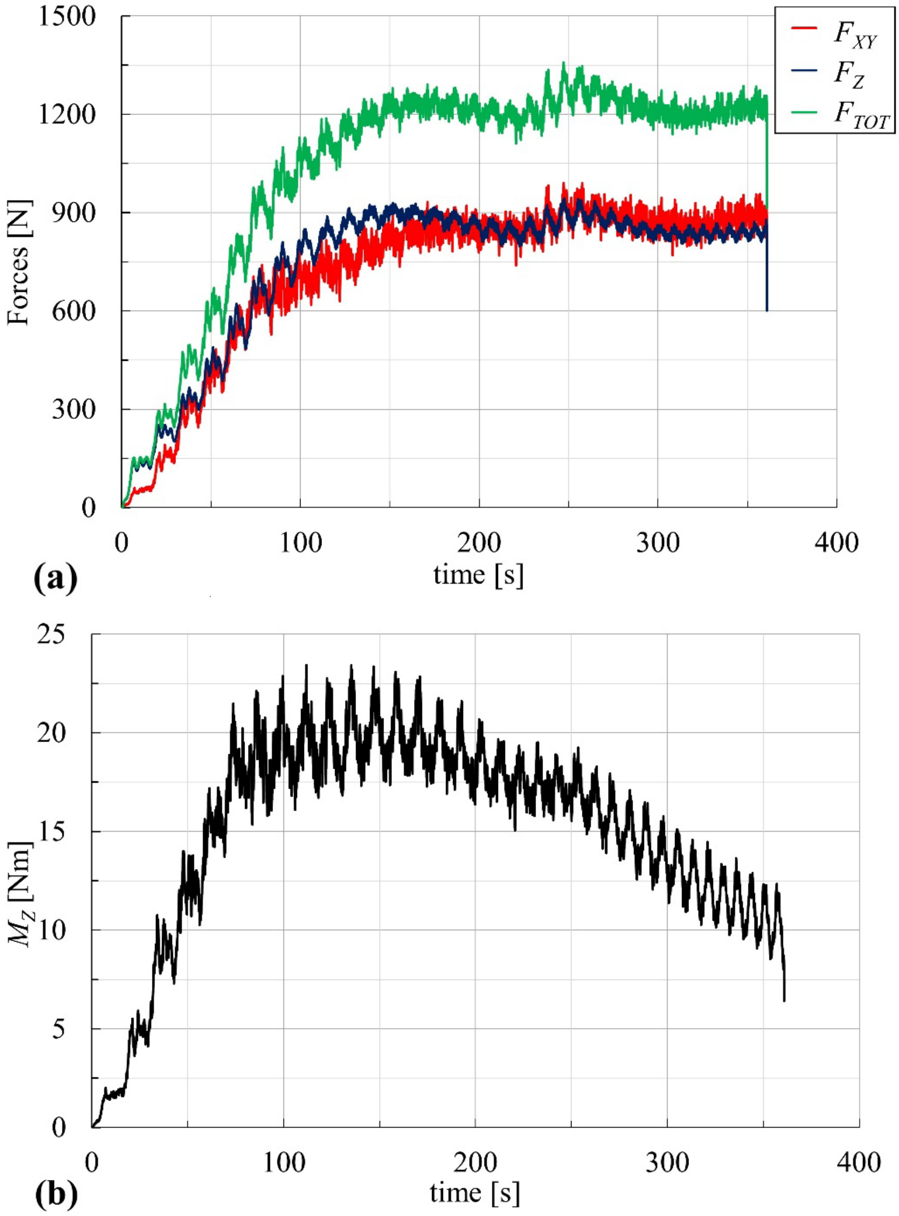


**Fig.4.** Trends of forces (a) and moment (b) during the incremental forming process of Nb sheets

Quantitatively, the forming forces remained low (one of the distinctive characteristics of the incremental forming process; $F_{TOT}$ did not exceed 1400 N). However, Fig. 4a reveals that the in-plane forces were comparable to the vertical ones, which is an uncommon outcome. It is worth noting that three components contribute to the in-plane forces, i.e. the thrust exerted on the cone wall, the friction resulting from the relative motion between the tool and the sheet and the flattening effect caused by vertical displacement [17]. While the first component was predictably low, being dependent solely on the combined shapes of the tool and the conical frusta, the other two components were relatively high. Fig. 5 illustrates the morphology of the worked surfaces. Despite the presence of lubricant, which reduces friction, the figure reveals scratches caused by galling. Additionally, the worked surfaces show technological imprints left by the forming tool. These signatures are particularly significant, also due to the considerable vertical indentation (surveyed by a mechanical feeler pin) left on the sheet, measuring 0.24 mm.

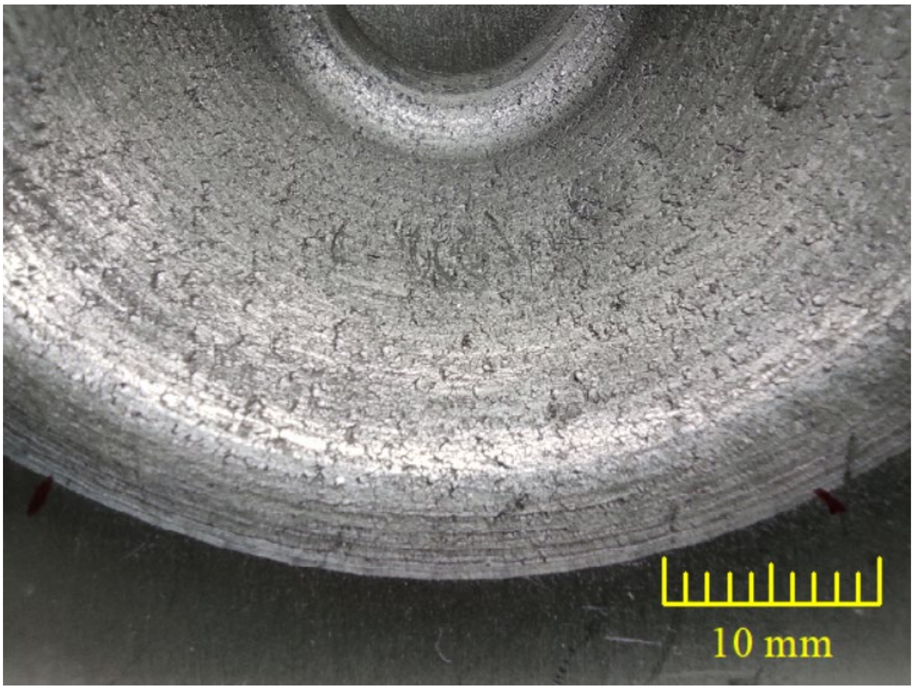


**Fig. 5.** Morphology of the worked surfaces

Concerning surface roughness, measurements yielded a mean roughness $R_a$ = 4.03 µm and a root mean square roughness $R_q$ = 5.20 µm. These values are significantly higher than those obtained from square frusta from fixed wall angle tests using pure Nb rolled sheets under similar working conditions, for which $R_a$ = 1.78 µm and $R_q$ = 2.26 µm [14].

As observed with incrementally formed grade 1 titanium thin sheets, where thermal oxidation treatments ensured high surface quality [13], the work hardening induced by rolling similarly benefits Nb sheets. This suggests the need to develop appropriate surface treatments. Indeed, according to the material datasheet, undeformed Nb sheets employed in this study exhibit a Vickers hardness of 51.5 HV, whereas hardness tests on the rolled sheets reported in [13] revealed increased hardness, ranging from 100.2 HV (after rolling) to 112.0 HV (after incremental forming).

## Conclusions and Future Work

This study presents an experimental investigation into the cold incremental forming of high-purity annealed RRR300 niobium sheets. The principal findings are as follows:

- Niobium sheets exhibit excellent workability under incremental forming conditions, demonstrating high formability and minimal defect generation;
- The total forming forces are low, although the in-plane and vertical components are comparable;
- The surface quality of the formed components is significantly affected by the inherently low hardness of niobium, showing technological imprint and scratches.

Developing surface treatment strategies to enhance the surface quality of incrementally formed niobium components represents a promising direction. Furthermore, future research could focus on simulating the forming process to enable a more comprehensive analysis of the process parameters.

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