Formability and surface quality of non-conventional material sheets for the manufacture of highly customized components

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Abstract

In this work, incremental forming of pure niobium planar isotropic sheets was studied; in particular, two different types of test were conducted by varying the tool/sheet contact conditions, in order to understand the complex phenomena interesting this hard-to-form non-conventional material and to focus the attention on its formability and the finishing of the worked surfaces. From the tests, the formability limits were determined, the forming forces were acquired and analysed, the quality of the worked surfaces was evaluated with measures of roughness and high-magnification visual inspection, as well as the failures of the sheets were observed and interpreted. The results highlight that a proper choice of the contact conditions can avoid the occurrence of galling while preserving an optimal carrying out of the process. In any case, very good surface finishing and workability of niobium sheets, despite their brittle nature, is found when incrementally formed. As a consequence, incremental sheet forming of this non-conventional material can be considered a faisable way of manufacturing highly customized components.

Keywords Incremental forming · Niobium · Contact conditions · Sheet metal formability · Wear

Introduction

Single point incremental forming (SPIF), i.e. the basic version of the incremental forming process requiring no dies and forming tools with simple shapes [1], is being extensively used as an alternative technique in sheet metal industry operations for the manufacture of components with symmetric and asymmetric shapes by using CNC machines [2].

This process, initially developed for the needs of car body manufacturers, is now used in many other industries, i.e., automotive, aerospace, marine and medical [3]; in addition, thanks to its high flexibility, SPIF is also considered as a viable solution for reshaping sheet metal End-of-Life components, in line with the principles of the circular economy [4].

In this process, the main parameters, namely the tool/sheet contact conditions (tool diameter, tool shape, use of lubricants, surface treatments, etc) and the tool path strategy (geometry, incremental step, feed rate, etc) are set to incrementally form sheets of pure metals, alloys, polymers and composites for the production of parts in fields requiring the production of customized components in a short time and at low cost.

The investigation of the tool/sheet contact conditions represents a very interesting topic when forming metals: for example, the choice of the lubricants affects the hardness of AA1100 incrementally formed components [5]; moreover, the formability of AA2024-O sheets can be increased through an opportune combination of shape and dimension of the forming tool [6].

All the more reason, this investigation is unavoidable for hard-to-form materials, like magnesium, titanium and their

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alloys [7]. Concerning this, a study on the warm incremental forming of AZ31 sheets demonstrated the necessity of developing lubricating method to give good solid lubrication performance and surface quality of components made of this magnesium alloy; furthermore, a previous authors' work highlighted that the formability limits of grade 1 titanium sheets can be improved by means of a thermal oxidation treatment of the worked surfaces [8].

Staying in theme of engineering materials, during the last decades, niobium (Nb) and its alloys are getting growing attention due to some intriguing properties: high room temperature ductility and melting temperature, exceptional strength at high temperatures and low thermal neutron absorption cross section; moreover, Nb exhibits the lowest density in the family of refractory materials [9]. What is more, Nb shows, among the superconductive elements, both the highest lower critical magnetic field (HC1) [10] and superconducting transition temperature [11], as well as a high normal state thermal conductivity [12].

Thanks to these properties, high purity Nb is used for the fabrication of superconducting radiofrequency (SCRF) accelerating cavities [13], superconducting sheets [14], pressure tubes for nuclear reactors and the chemical process industry [15] and so on [16]. Among these applications, the production of SCRF cavities is probably the most challenging and intriguing. Their performances are sensitive to the Nb chemical and physical properties as well as the microstructure, so much that a well defined and controlled processing route must be used to fabricate these components. Traditionally, these components were produced joining, by electron beam welding, sub-components obtained by deep drawing; but freshly, because of the request of more powerful accelerators, new production processes for manufacturing high performances cavities are considered, like explosive forming, tube hydroforming, spinning of deep drawn or spun tubes and combined process (e.g. swaging and tube hydroforming) [17]. It is also interesting to recall that this kind of product, the SCRF cavities, is fabricated in extremely small batches (sometimes only one cavity for each batch); so, to design a proper processing route and to ensure the high properties required, it is mandatory to understand the behaviour of the material and to develop reliable constitutive and mathematical models [18].

Coupled with the above mentioned intriguing and unique properties, Nb also shows some peculiar behaviours that need to be understood to design the processing routes properly. In fact, it was proved that aiming to ensure good formability, some aspects are of primary interest for Nb [19].

One of the main issues in forming of high purity Nb is its anisotropy that could undermine the achievement of symmetric and uniform cavities during deep drawing process. It was found that the anisotropy coefficient of high purity Nb decreases with the plastic strain and is also strongly

influenced by the texture [20]. Kim et al. [21] obtained interesting insight on the plastic behaviour of Nb by studying the stress-strain curves by compression and tension of nanopillars; they observed that the compression curves present a number of discrete segments showing intermittent strain bursts, while the tension ones show reduced plasticity, with elongation at failure equal to 3%. This suggests that Nb shows a kind of Portevin-Le Chatelier effect [22] under certain loading conditions, due to the pinning of the dislocations against preferential glide planes.

The complex role of dislocations in Nb forming and their interactions with the lattice were elucidated in [23]; they found that the processing conditions strongly influence the dislocation formations and, subsequently, the physical properties (which are of great deal of interest for high energy applications) of Nb parts.

Kommel [24] observed that severe plastic deformation reduces the electrical conductivity of Nb, suggesting that the dislocations obstacle the movement of the electron. They also observed a softening of the material and a decrease of the Young modulus when the strain rate increases during plastic deformation; this outcome was explained by Kommel et al. [25] on the basis of the interatomic attraction forces in the lattice.

Surface finishing is also a primary requirement in the SCRF cavities; a perfect mirror-like surface is required to ensure the proper behaviour of the cavities when in service [26]. Nb presents unusual surface properties; for example, when the grain size is small and uniform, it ensures good formability and circumvents, after a deep drawing process, too high surface roughness (resulting in an orange peel effect), as a consequence of the non-uniform deformation of large grains showing different crystalline orientation [27]. Consequently, a prediction of the surface finishing results difficult [28], as well as of the friction coefficient to set in equations for the process modelling [29].

Bringing together all the discussed literature, three point can be of particular interest for this work: i) the fabrication of components like SCRF cavities is a small batch/high variability production process; ii) Nb has good formability, but the pronounced anisotropic behaviour can lead to inhomogeneities in the formed part; iii) a poor tribological behaviour of Nb is observed, so to ensure the desired surface finishing particular attention must be paid during the forming process. On these premises, it can be interesting to investigate the incremental forming of planar isotropic Nb sheets: first of all, this forming process is particularly prone to high variability-small batch production [30]; secondly, the tool/sheet contact conditions can be tailored to achieve the desired surface finishing [31].

In a previous work [32], the authors highlighted the strong influence of the tool/sheet contact conditions and the importance of their choice for a correct carrying out of

the incremental sheet forming of Nb parts; these considerations were made in light of an experimental campaign by using one only forming tool type (a hemispherical tipped tool) and one only shape of the components (fixed slope angle cone frusta).

The scope of this paper is to increase understanding related to the incremental forming of planar isotropic Nb sheets, taking into account further tool/sheet contact conditions and features; in detail, qualitative and quantitative evaluations of the formability limits, the forming forces and the roughness of the worked surfaces were made, as well as an interpretation of failures interesting the sheets. To this end, variable slope angle cone frusta and fixed slope angle square pyramid frusta were manufactured by SPIF, and the results from an experimental campaign on dry and lubricated sheets, formed with two different forming tools, were compared.

Fig. 1 Engineering stress-strain curves obtained through the tensile tests

Fig. 2 Scheme of the experimental setup adopted for the forming tests: clamped sheet and components of the forming forces

Materials and methods

Pure Nb rolled sheets, thick $t=0.5$ mm, were tested; their chemical composition is fully available in [33]. They were obtained by the cold-rolling of parent sheets ($t_0=3.0$ mm in thickness). The thickness reduction was performed by means of an electric flat rolling mill [34] along two directions, perpendicular to each other; it was obtained by many reduction steps, that alternate along the two directions, each of which equal to $rs=0.25$ mm. In this way, they can reach an almost planar isotropy; as a confirmation of this and of the reproducibility of the outcomes, you can see in Fig. 1 the engineering stress-strain curves from tensile tests carried out by using an MTS universal testing machine, following the ASTM E8 standard and along two mutually perpendicular directions (labelled as dir1 and dir2). A brittle behaviour can be highlighted (elongation at failure $\varepsilon_f=3.6\%$); furthermore, a yield stress $Y=258$ MPa, an ultimate tensile strength $UTS=283$ MPa and a Young modulus $E=107$ GPa are also measured.

The SPIF was carried out by means of a high speed vertical machining center C.B. Ferrari at room temperature. Pieces of sheets ($L_s^2=140\times140$ mm²) were clamped peripherally by a frame with an internal square area, $L_f=100$ mm side. This last was fixed on the table of the CNC machine. A schematic of an incremental formed sheet and the clamping frame is reported in Fig. 2 (for the sake of drawing readability, only one half of the clamping frame is represented).

The influence of the tool/sheet interaction on the process was assessed planning tests in dry and lubricated conditions (for this last case, Reactolab industrial grease was used) and varying the forming tool: specifically, a hemispherical tipped tool and a roller-ball tool (a CAD model of which is reported in Fig. 3a and b, respectively) were used. They are both of stainless steel, with a diameter of 10 mm, and were held by the CNC machine spindle. Different tests were carried out using the hemispherical tipped tool both in dry and lubricated conditions and the roller-ball tool in lubricated

Fig. 3 CAD model of hemispherical tipped (a) and roller-ball tool (b) used in this experimentation

condition, in order to ensure the correct ball rolling in its housing. In the rest of the text, the three tool/sheet contact typologies are labelled as follows: HT (dry) for hemispherical tipped tool in dry condition, HT (grease) for hemispherical tipped tool in lubricated condition and RB for roller-ball tool in lubricated condition.

The experimental campaign involved the manufacture of two types of components: cone frusta with variable slope angle (variable slope angle tests) and square pyramid frusta with fixed slope angle (fixed slope angle tests), in a number of three for each contact condition. A CAD representation of the two geometries is reported in Fig. 4a and b, respectively (the representation of the two consecutive spirals of the tool path for the indication of the angular and vertical steps is not in scale, for the sake of drawing readability). All the components were obtained setting helical tool paths described at a feed rate $f=3000$ mm/min, clockwise around the z-axis in respect of the right hand rule.

Variable slope angle tests were performed to determine the influence of the contact conditions on the formability limits of the Nb sheets, in terms of maximum slope angle achievable on geometries (cone frusta) without geometrical singularities (like the ribs of pyramid frusta) and for which this feature increases continuously as the process progresses; in so doing, it is possible to investigate this feature in one only test, rather than a series of fixed slope angle tests with increasing angle. These destructive tests were carried out by following what was done by [35]: they ended to the onset of fractures; following this, the evaluation of the maximum slope angle (α_{max}) was made by means of geometrical measures in correspondence with the failure z-position.

They state that the slope angle of the walls starts from an initial value $\alpha_0=45^\circ$ and the incremental angular step between two consecutive spirals of the tool path was $\alpha_s=0.5^\circ$; in doing so, the components take the shape of a cone frustum, with the radius of the major base $R=35$ mm, and the lateral surface of a circular cylinder, with generatrix radius $R_g=50$ mm.

The fixed slope angle tests, for which an incremental vertical step between two consecutive spirals of the tool path $vs=0.5$ mm was chosen, were carried out to measure the forming forces and the quality of the worked surfaces. The components manufactured in these tests (side of the major base $L=70$ mm, slope angle $\alpha=60^\circ$ and height $h=39$ mm) present flat walls that allow easy acquisition of roughness; moreover, the straight lines of the tool paths along the walls allow to distinguish between the forces linked to the thrust of the forming tool on them and the ones linked to friction and flattening of the feed rate.

The measurement of the vertical component (F_z) and one only horizontal component (F_y) of the forming forces was carried out by means of a piezoelectric transducer (Kistler 9257A) completed with a NI 9239 input module and the

Fig. 4 CAD model of cone frustum with variable slope angle (c) and square pyramid frustum with fixed slope angle (d)

VBA 1.0 B software; the data were filtered following their acquisition at 2000 Hz. Figure 2 schematizes these components on two adjacent walls of the frusta (labelled as A and B).

A comparison in terms of forces was conducted in steady-state and far from the ribs, then only in the central area of the walls (in so doing, excluding the peaks that reveal the interaction of the tool with the ribs). Under the assumption of planar isotropy of the sheets, one only wall for each spiral of the tool path (in this work, the wall B was chosen) is enough to describe the vertical component of the forming force; on the contrary, two adjacent walls must be considered for the horizontal one (A and B; the other two show almost the same absolute values). In detail, for the wall A, the lines of the tool path and the horizontal channel of the acquisition system are parallel; this channel records a force from two contributors: the first one for flattening the sheet as a consequence of the vertical displacement and the second one lied to the friction between the tool and the sheet; concerning the wall B, for which the lines of the tool path are perpendicular to the horizontal channel acquisition direction, the force is lied to the thrust on the pyramid walls [8].

The surface quality was assessed by high-magnification visual inspection and by measuring different linear roughness parameters along the cross-section of the worked surfaces, more specifically: the mean roughness (R_a); the root mean square roughness (R_q); the maximum height of the profile (R_y); the mean roughness depth (R_z). A Mitutoyo SurfTest SJ-301 tester was used; five measurements for each contact condition, but also on undeformed sheets, were taken, following the ISO 4288 standard.

All relevant information about the experimental setting is summarized in Table 1 (equipment and tool/sheet contact conditions) and Table 2 (experimental setup).

Results and discussion

This section reports the main results from the experimental tests. In particular, the outcomes in terms of formability limits from the variable slope angle tests, and of forming forces and surface quality from the fixed slope angle tests were discussed, as well as an interpretation of the different sheet failures was done.

Formability limits

Figure 5a shows an example of variable slope angle test stopped at the failure occurrence (in correspondence of which α_{max} was evaluated), in the specific for the HT (grease) condition; moreover, Fig. 5b reports the corresponding diagram of the vertical force, showing the reduced forces when the tool passes over the fractured parts.

Table 1 Equipment and tool/sheet contact conditions

Sheet	
Material	Niobium
Behaviour	Planar isotropy
Parent thickness, t_0	3 mm
Reduction steps, r_s	0.25 mm
Thickness, t	0.5 mm
Area, L_s^2	140 × 140 mm ²
Young modulus, E	107 GPa (dir1); 107 GPa (dir2)
Yield stress, Y	259 MPa (dir1); 257 MPa (dir2)
Ultimate tensile strength, UTS	282 MPa (dir1); 279 MPa (dir2)
Elongation at failure, ϵ_f	3.60% (dir1); 3.61% (dir2)
Forming tools	
Material	Stainless steel
Diameter	10 mm
Typologies	Hemispherical tipped tool Roller-ball tool
Clamping frame	
Internal area, L_f^2	100 × 100 mm ²
Lubricant	
Description	Reactolab industrial grease
Tool/sheet contact conditions	
Typologies	Hemispherical tipped tool/sheet in dry condition, HT (dry) Hemispherical tipped tool/sheet in lubricated condition, HT (grease) Roller-ball tool/sheet in lubricated condition, RB

From the variable slope angle tests, it is possible to affirm that the tribological aspects influence the formability limits; in fact, while α_{max} values for HT (grease) and RB tests are practically the same (74.7°), for HT (dry) this feature decreases significantly (α_{max} = 64.7°). Anyway, these values highlight significant incremental formability of the material tested; in fact the α_{max} values are comparable with the ones of very ductile materials like, for example, AA7075 sheets tested in a similar way in a previous authors' work [36], even more so if considering the brittle behaviour of Nb highlighted by the tensile tests. This can be ascribable to the good response of the material to multiaxial stress and its strain rate sensitivity. Pan et al. [37] observed either flow softening or work hardening depending on the forming conditions, in particular they reported flow softening for all of the dynamic stress-strain curves. Still, for a given level of strain, the flow stress keeps growing with the deformation and does not show relevant saturation. This accounts for the observed strain rate sensitivity.

What is more, as recalled in the Introduction section, the formability of Nb is strongly influenced by the texturing and by some complex phenomena, i.e. the Portevin-Le Chatelier effect [22]; so, it is reasonable that different tribological

Table 2 Experimental setup

Variable slope angle	
Component geometry	Cones with variable slope angle
Initial slope angle, α_0	45°
Angular step, α_s	0.5°
Radius of the major base, R	35 mm
Generatrix radius, R_g	50 mm
Tool path characteristics:	
Geometry	Elical
Feed rate, f	3000 mm/min
Direction	Clockwise around the z-axis
Features analysed	Maximum slope angle, α_{max} Failures typologies
Fixed slope angle	
Component geometry	Pyramid frusta with fixed slope angle
Slope angle, α	60°
Vertical step, v_s	0.5 mm
Side of the major base, L	70 mm
Height, h	39 mm
Tool path characteristics:	
Geometry	Elical
Feed rate, f	3000 mm/min
Direction	Clockwise around the z-axis
Features analysed	Vertical component of the forming forces, F_z Horizontal component of the forming forces, F_y Mean roughness, R_a Maximum height of the profile, R_y Root mean square roughness, R_q Mean roughness depth, R_z Failures typologies Morphology of the worked surfaces

conditions will result in different deformation behaviour of the material. Looking at Fig. 5b, some oscillations can be seen; these oscillations can also be produced by the pinning of dislocations against the atoms of the lattice, as observed in previous work carried out on Nb.

However, it is worth pointing out that with the variable slope angle tests there is an overestimation of the sheets formability compared to the maximum angles reachable with fixed slope angle tests. This discrepancy can be attributed to the process conditions of the fixed slope angle tests that are heavier; in fact, the angle does not start from lower values and, moreover, the presence of geometrical singularities like the ribs represents a critical issue [38].

In light of the considerations above reported on the formability limits, the slope angle chosen for the fixed slope angle tests (equal to 60°) was reasonably lower than the lower value of α_{max} recorded from the variable slope angle tests. The main results from these tests are reported in the following subsections. Another interesting result was the softening at high strain rate flow; this can be consequent to the rise of the adiabatic temperature, which usually occurs in viscoplastic materials subject to dynamic loading. Croteau et al. [39] in late 2020 published an interesting paper investigating

the deformation behaviour of Nb single crystals and Nb sheets with a coarse grain size. They also observed a high strain rate softening and a marked anisotropic behaviour during deformation.

Forming forces

The steady-state condition of the forming forces was reached for all the tool/sheet contact conditions after a depth of about 5 mm; by way of example, see Fig. 6 related to a HT (grease) fixed slope angle test. Contrary to the tests in lubricated conditions, carried out in a sound way up to the designed height, the HT (dry) tests failed after reaching the steady-state, for a height of about 15 mm; consequently, they were prematurely stopped.

In light of above, the considerations on the forming forces were made for a z-displacement between 5 mm (start of the steady-state) and 15 mm (failure occurrence for HT (dry) tests). Figure 7 shows the trends of the two components of the forming forces (F_z , Fig. 7a, and F_y , Fig. 7b) in steady-state and at equal z-displacement (≈ 8 mm); you can note that F_z , and F_y along wall B albeit on a smaller scale, are similar for all the contact conditions, with average values in the

Fig. 5 HT (grease) variable slope angle test: failure occurrence (a) and force monitoring (b)

Fig. 6 Trend of the components of the forming forces during a HT (grease) fixed slope angle test

inspected area of about 370 and 85 N, respectively. They are lied to the trust on the sheet and, then, to the designed geometry of the components; consequently, under the same slope angle and for similar shapes of the forming tools, significant differences for these components cannot be expected. The

Fig. 7 Vertical (a) and horizontal component of the forming force (b) in steady-state of a fixed slope angle test

value of these components are influenced by the behaviour of tool and sheet and in particular, by assuming as rigid the tool, by the mechanical properties and the thickness of the sheet. On the other hand, F_y along wall A is influenced strongly by the tool/sheet contact conditions, so it results significantly lower under RB conditions (rolling friction; average value of about 80 N); the other two conditions (sliding friction) not only determine significantly higher force values (in line with the considerations on the friction coefficients reported in [40]; average value of about 350 N), but also show an irregular trend (in line with the results of a similar authors' study on another hard-to-form material, i.e. the grade 1 titanium [8]), and both these aspects are more relevant for HT (dry) tests.

Surface analysis

Figure 8 reports some images of the worked surfaces for the different contact conditions, whereas Table 3 summarizes the mean values of the measured roughnesses (with the corresponding standard deviations between round brackets).

The use of the hemispherical tipped tool (Fig. 8a to c) involves a scratched surface as a consequence of the overlay

Fig. 8 Wear (a) and failure (b) on a HT (dry) surface; wear on a HT (grease) (c) and a RB surface (d)

Table 3 Values of the roughness parameters

Contact conditions	Roughness parameters [μm]			
	R_a	R_q	R_y	R_z
HT (dry)	5.32 (0.52)	6.43 (0.65)	28.33 (3.37)	19.17 (3.59)
HT (grease)	1.78 (0.17)	2.26 (0.25)	11.74 (1.11)	7.74 (0.82)
RB	0.75 (0.04)	0.92 (0.06)	4.44 (0.13)	2.80 (0.16)
Undeformed	0.38 (0.04)	0.48 (0.04)	2.85 (0.09)	1.93 (0.05)

of wear with the technological marks. In particular, the sheets are subject to the galling phenomenon; it represents a typology of adhesive wear, as the result of the macroscopic material transfer between metal surfaces, following their relative sliding motion [41]. As a consequence, the component of the forming force lied to the tool/sheet relative motion (F_y along wall A, see Fig. 7b) results irregular; moreover, the sheets worked under HT (dry) conditions are strongly affected by galling, so as shown in Figure 8a.

The inspection of the surfaces worked by the roller-ball tool (Fig. 8d) reveals that the adhesive wear is negligible, while the technological signatures that the forming tool leaves along its path are observable. As a consequence, the galling is not present for this working condition.

Table 3 confirms that there is a significant improvement of the quality going from using a hemispherical tapped tool in dry condition to a lubricated roller ball; in fact, the first

solution shows values of the roughness parameters about seven times bigger, and more variable, than the corresponding ones of the second solution. Besides, this latter allows obtaining a slightly worse surface quality than the one of the undeformed sheets (with R_a equal to 0.75 and 0.38 μm , respectively). In any case, all the working conditions guarantee R_a values that, following the ISO 4287/1 standard, fall into the range typical of machined or hand grinded surfaces.

Failures typologies

As anticipated above, it is evident that the HT (dry) conditions are the most severe; in fact, they represent the only contact condition for which failures the fixed slope angle tests were not carried out in a sound way. Figure 9 shows the cracks occurring on the sheets from a HT (dry) fixed slope angle test. You can note that the failures interest not only a limited zone near the ribs, typical of incremental sheet forming of metals [42], but also other zones far from the ribs and subject to less severe work conditions (atypical failure; they occurred a few toolpath spirals before the occurrence of the typical failure). Besides, Fig. 8a highlights that these sheets are so much affected by galling that the scratches can condition the occurrence of failures (see Fig. 8b); concerning this, see the high R_y and R_z values reported in Table 3. This can limit the formability of the sheets, even more so if considering their small thickness and thinning resulting to

Fig. 9 Failures interesting a square pyramid frustum from an HT (dry) fixed slope angle test

the deformation process, presumably in agreement with the sine law [43].

On the contrary, by observing the failure that develops along a circumference going on the tool path from a HT (grease) variable slope angle test (see Fig. 5a), you can expect only typical metal sheet failures for the lubricated sheets [42].

Conclusions

The incremental forming of pure niobium thin rolled sheets with planar isotropic behaviour was investigated in this work. The experimental campaign included the production of variable slope angle cones and fixed slope angle pyramid frusta, obtained under different contact conditions: the process was conducted by using a hemispherical tipped tool both in dry and lubricated conditions and a roller-ball tool in lubricated condition; industrial grease was used as a lubricant.

The main results of the experimental campaign can be summarized as follows:

- The variable slope angle tests highlight that the sheets show very high workability when incrementally formed, similar to ductile metal alloys, despite their brittle behaviour under tensile tests. The formability limits are significantly lower in dry conditions (maximum slope angle of about 65°), while the tool type is not influential in lubricated conditions (maximum slope angle of about 75°). Moreover, this kind of test overestimates the formability limits, compared to the maximum angles reachable with fixed slope angle tests, especially in dry conditions;

- From the fixed slope angle tests, the tool/sheet contact conditions strongly influence the rate of forming force lied to friction. In detail, sliding friction when using the hemispherical tipped tool translates into significantly higher force values (with an irregular trend), even if in dry conditions, as a consequence of very high friction coefficients;
- The fixed slope angle tests also furnish information on the surface quality and the occurrence of failures. All the contact conditions guarantee very low roughness values of the worked surfaces, with the mean roughness always less than 6.0 μm , comparable to that obtained by machining or hand grinding. Despite this, sliding friction generates scratches as the effect of the galling. This adhesive wear phenomenon can limit the formability limits through the premature occurrence of failures in unexpected zones, but it can be strongly reduced by using the roller-ball tool.

The excellent formability of the sheets suggests, as future work, the proper investigation of their mechanical properties depending on the strain rate; this can be useful, along with the determination of the friction coefficient for the tool/sheet contact conditions typical of the incremental sheet forming, for correct implementation of numerical models in FE ambient.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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