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Thermal Effects on Tribological Behavior in Machining Natural Fiber Composites

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Abstract

Machining natural fibers reinforced plastic (NFRP) composites is nowadays a real challenge for academia and industries. These eco-friendly materials are emerging in automotive and aeronautical industries thanks to many benefits for sustainable development. It is then necessary to anticipate their machining processes for integrating them into the NFRP industrial production chains. This paper investigates the thermal effect on the machinability of unidirectional flax fibers reinforced polypropylene composites (UDF/PP) regarding to the cutting contact geometry. For this aim, orthogonal cutting process has been performed on UDF/PP composites at room and low temperature of composite samples. Cutting contact geometry has been explored by changing the tool rake angle. Results show that reducing the cutting temperature affects the chip morphology and improves the cutting behavior of flax fibers which ameliorates the machinability of UDF/PP composites. This machinability is also improved by cutting with a smaller positive rake angle that increases the cutting contact stiffness with flax fibers. This study allows determining a new relevant indicator parameter of NFRP machinability based on the cutting friction.

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Keywords: Flax fibers; Thermoplastic composites; Orthogonal cutting; Cutting temperature; Tool rake angle; Surface roughness.

1. Introduction

Environmental constraints are becoming more severe in order to limit the pollution of our planet. In this context, industrial demands on eco-friendly materials increase significantly to meet the environmental standards. Therefore, natural fiber reinforced plastic (NFRP) composites are emerging automotive and aerospace industries to compete with synthetic fibers composites performed with glass fibers [1–3]. Indeed, some natural fibers extracted from plants, such as flax, hemp, ramie or jute, can challenge synthetic glass fibers in terms of mechanical properties [2,4] vibration damping [5,6], acoustic and thermal insulation [7], in addition to their both biodegradability and recyclability that make them advantageous for circular economy and sustainable development [8].

The integration of these eco-friendly materials in industrial products requires finishing operations for converting them to the final industrial application. Machining processes, such as drilling or edge milling, remains then unavoidable in the manufacturing process of NFRP composites. Thus, understanding and optimizing the machining process of NFRP composites is required to close the loop of the industrial NFRP production chain.

For these reasons, NFRP machining using edge milling process was investigated by previous authors works [9–12] that show the specific issues of cutting plant fibers inside thermoplastic composites. Indeed, the multiscale cellulosic structure of plant fibers [13] gives them a high transversal flexibility inside the composite and allow them to deform easily during the cutting contact, which makes there shearing difficult [12]. As consequence, the fiber shearing is not efficient and some uncut fiber extremities remain on the machined surfaces which increase the surface roughness [10–12]. Moreover, rating the machined surfaces of NFRP composites requires the selection of the pertinent scales that allow the discrimination of both material and process effects. This is because plant fibers have multiscale mechanical properties that are intimately dependent on the mechanical analysis scale [14].

Therefore, due to the high transverse flexibility of natural fibers, optimizing the machinability of NFRP composites means improving the cutting contact stiffness. The contact stiffness can be increased by changing the contact geometry and/or increasing the rigidity of materials in contact. In this context, two parameters may appear significant for NFRP machinability: tool rake angle and material temperature. Indeed, cutting rake angle modifies the cutting contact geometry and can affect the nature of tool/material engagement. Literature studies on machining carbon fiber composites [15–17] and glass fiber composites [18–20] investigate the rake angle effect on cutting forces. For carbon fiber composites, the rake angle influence is dependent on the fiber orientation and its effect is insignificant when carbon fibers are oriented perpendicularly to the cutting direction [15]. The rake angle effect is more obvious on thrust forces [17] and it affects slightly the surface roughness which is better when cutting with positive rake angle [16]. However, glass fiber composites are more affected by cutting rake angle, where increasing the rake angle decreases the cutting force [18,19].

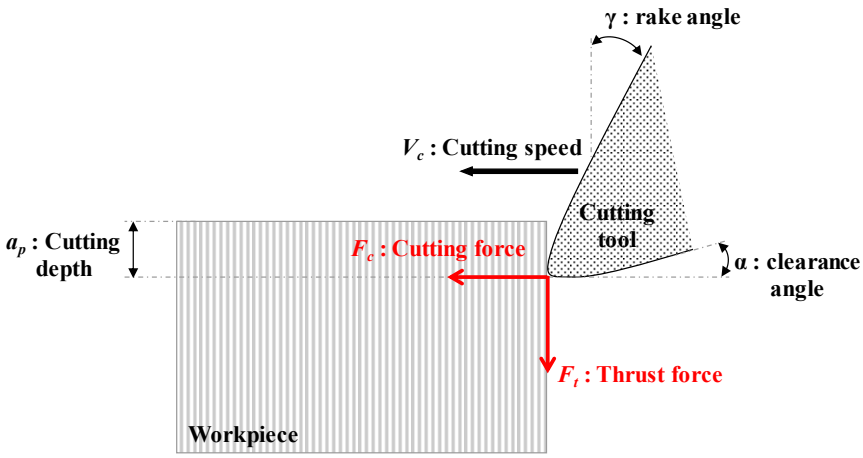

Fig. 1. Schematic depiction of orthogonal cutting operation

This may be due to the high rigidity difference between carbon fibers and glass fibers. Indeed, the high carbon fibers rigidity controls the cutting contact stiffness rather than the cutting contact geometry. For NFRP composites, only short wood fiber composites have been tests and they show a decreasing of cutting forces by rake angle increasing [21]. Unfortunately, the effect on long NFRP composites is still misunderstood.

On the other side, the high material deformation speed in machining induces a high temperature at the cutting contact zone. This can significantly affect the cutting behavior by changing the cutting contact properties. A little understanding on this field exist nowadays in the literature for synthetic fibers composites. Indeed, for carbon fibers composites, it has been demonstrated that increasing the cutting speed increases the cutting temperature during drilling operation to reach around 200-350 °C [22]. The thermal effect is essentially observed in the polymer matrix that behaves differently depending on its thermal properties (heat dissipation, thermal conductivity, and thermal stability) [23]. It has also been shown that machining carbon fiber composites under low temperature reduces the cutting temperature and cutting resistance as well as the burrs and fuzzing in the upper and lower plies of the specimen [24]. However, no work has investigated the thermal effect on NFRP machining. Unlike synthetic fibers, natural fibers are themselves a composite material of cellulose microfibril embedded in amorphous natural polymers of hemicellulose and lignin [9,13] that are temperature dependent [25]. Therefore, the thermal effect can be more significant for machining NFRP materials.

Thus, this paper will focus on the combined effects of tool rake angle and sample temperature when cutting unidirectional flax fibers reinforced polypropylene composites (UDF/PP). This study will allow investigating how these two important parameters can affect the cutting contact stiffness and, then, the cutting behavior of NFRP composites. For this aim, the in-situ cutting forces and chip formation are recorded at each cutting condition. The machined surface state is evaluated with scanning electron microscopy (SEM) observations and the induced surface roughness is rated using optical interferometer.

2. Material and method

Orthogonal cutting process is a particular case of a cutting configuration. Orthogonal cutting principle is respected when the material is machined with one straight edge perpendicular to the feed direction which is given by the cutting speed (V_c) as shown in Fig. 1. Orthogonal cutting geometry is intimately dependent on the cutting tool position regarding the considered workpiece. This position is defined by a rake angle (γ), a clearance angle (α) and a cutting depth (a_p) as described in Fig. 1. Orthogonal cutting is mainly used in scientific investigations because it involves the basic physical phenomena present during a cutting operation. Moreover, it allows a good discrimination of elementary cutting mechanisms to simplify the analytical and numerical modeling.

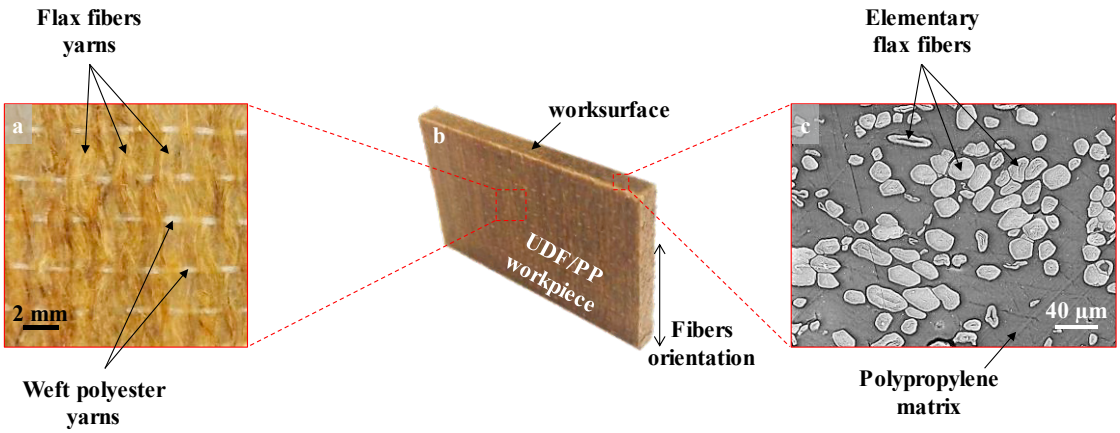

Fig. 2. (a) Flax fibers reinforcement structure. (b) Photograph of UDF/PP workpiece. (c) SEM image of the UDF/PP worksurface

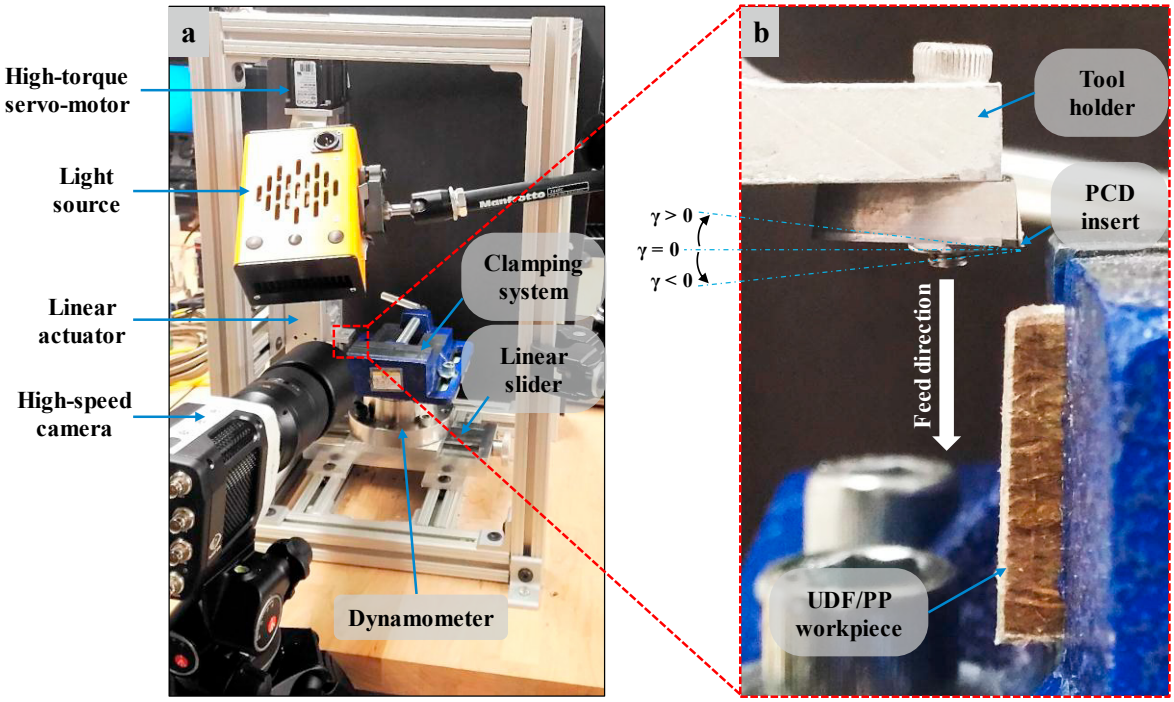

Fig. 3. (a) Photograph of the whole experimental setup. (b) Photograph showing the PCD insert position against the workpiece.

To perform the orthogonal cutting study, the UDF/PP workpieces shown in Fig. 2(b) are manufactured and supplied by "*Composites Evolution – UK*". The fiber volume fraction is 40% and their unidirectionality is maintained by polyester weft fiber with low volume fraction (around 5%) as shown in Fig. 2(a). The fiber distribution in the composite is not homogeneous because of the variability of both the fiber bundles size and the elementary fibers shape as shown in Fig. 2(c). More technical data of UDF/PP composites is given in [12]. The workpieces dimension is 20×15×4 mm and the fibers are oriented perpendicularly to the cutting direction. Each workpiece has its worksurface polished with the same grit size (~ 15 µm) to perform similar initial conditions before cutting tests.

Fig. 3(a) illustrates the experimental setup for the orthogonal cutting of UDF/PP samples in order to obtain chip morphology as well as cutting forces. The setup consists of two linear sliders and a dynamometer. The cutting tool is attached to one linear actuator through a customized tool holder. The linear actuator (L70, Moog Animatics, Milpitas, CA) is driven by a high-torque servo-motor to maintain a constant feed rate during cutting. The force dynamometer (Model 9272, Kistler, Winterthur, Switzerland) is used to capture high-speed or high-frequency force data up to 5,000 Hz. Data collection is performed via an amplifier, a shielded connector block, and a data acquisition device (PCIe-6321, National Instruments, Austin, TX), along with a data recorder, LabVIEW, at 2000 Hz sampling rate. The workpiece is fixed via a clamping system on the top of the dynamometer which is placed on the other linear slider manually adjusted to the depth of cut for each test. As shown in Fig. 3(b), the workpiece is held stationary, and the cutter is moved at a constant velocity of 6 m/min. The total cutting length is about 15 mm.

Cutting tool is provided by "Sandvik Coromant – FR" (Model TCMW16T304FLP – CD10). The considered cutting tool has a tungsten carbide substrate and a polycrystalline diamond (PCD) insert as a cutting edge (see Fig. 3(b)). The aim of using PCD insert is to have the sharpest cutting edge with the highest mechanical performances because NFRP composites are extremely sensitive to the cutting edge radius when machining as demonstrated in [12].

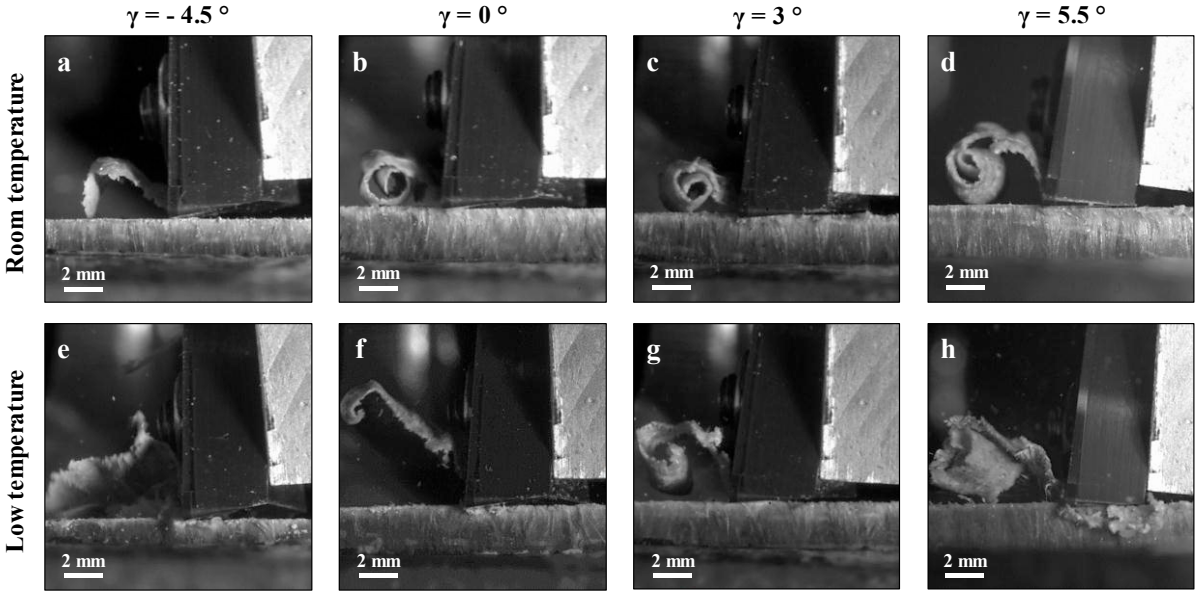

Fig. 4. Chip formation morphology obtained by high-speed camera for the different cutting conditions.

The PCD cutting tool has a zero-rake angle and a clearance angle of 7°. Changing the rake angle is made by tilting the cutting tool from its initial position that is perpendicular to the feed direction. Thus, four values of rake angle are considered (γ = -4.5˚, γ = 0˚, γ = 3˚ and γ = 5.5˚). Positive rake angle values are limited at this range to not reach a zero-clearance angle and avoid the contact between the machined surface and the clearance tool face.

To investigate the effects of sample temperature, tests are carried out under the room sample temperature and a low sample temperature. The room temperature is about 22°C. Low temperature is performed by cooling the workpiece using a freezing spray. To maintain the low temperature for corresponding cutting tests, a freezing spray is applied on the worksurface for 20 seconds. The temperature right after the end of spraying is about -10°C. Then, the cutting procedure takes about 5 seconds to start. Consequently, the real workpiece temperature right at cutting start is between 0° and 5°C. The sample temperature is measured by a thermocouple placed on the worksurface.

To capture the chip morphology, a highspeed camera (Phantom Miro Lab310, Vision Research Inc.,Wayne, NJ) is used along with appropriate lightening. The highspeed camera is set with 640×480 resolution, 1000 fps, and 1000 µs exposure time to capture the best view of chip formation.

After orthogonal cutting experiments, machined surfaces states are evaluated by scanning electron microscope (Zeiss SEM – model EVO/MA10) at low vacuum mode (40 Pa of chamber pressure). SEM images are taken at different locations on the machined surfaces and typical representative surface morphology as induced by orthogonal cutting is hence presented in this study. Moreover, the polished surfaces topography is rated using the optical interferometer (Model ZYGO/14-21-75092) using a magnification of ×10. Topographic images are taken in five different location of each machined surface to determine the arithmetical mean height of the surface (S_a) following the ISO 25178 standard.

To get reliable results, each considered cutting test is repeated three times under identical conditions and with a new cutting tool at each time. Thus, the output values from orthogonal cutting experiments are presented as the mean of these three repeated tests. Errors are considered as the average of the absolute deviations of data repeatability tests from their mean.

3. Results and discussions

3.1. Chip formation of UDF/PP composite

Fig. 4 illustrates the chip morphologies obtained by orthogonal cutting. The removed chip remains continuous at all the cutting conditions. However, the chip shape differs by changing the rake angle and

lowering the temperature. Indeed, increasing the rake angle toward positive values favors the chip curling. Nevertheless, lowering the workpiece temperature prevents the chip curl.

The chip continuity is mainly due to the high shearing ductility of UDF/PP composites induced by both the ductility of PP matrix and the high transverse flexibility of flax fibers as demonstrated by Iosipescu

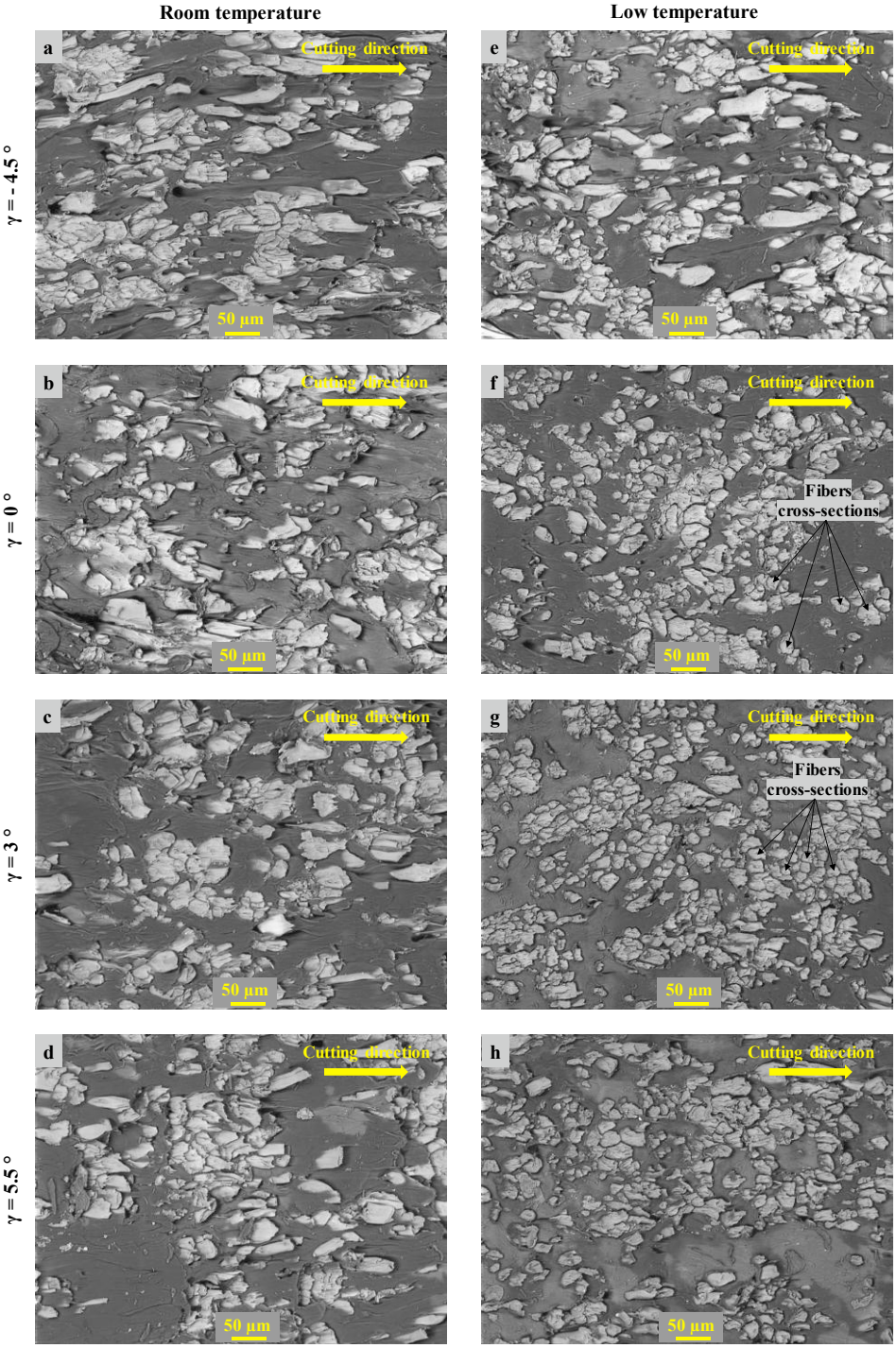

Fig. 5. SEM images of machined surfaces showing the fibers cutting behavior of UDF/PP at different cutting conditions

shear tests in [26]. This specific behavior allows flax fibers to follow the PP deformation during the cutting operation and, consequently, avoids the brittle fracture between flax fibers and PP matrix in the removed chip.

Rake angle is among the important parameters that control the chip formation. Rake angle defines the rake face position that leads the chip flow. Increasing the rake angle gives the chip a spatial ability to curl. However, the chip curling is mainly a thermomechanical phenomenon. Both larger strains due to friction-induced deformations and thermal expansion at the tool rake face lead to a curling of the chip [27]. Indeed, the curling mechanism is initiated by a transversal deformation of the chip that is due to the temperature difference between the two chip faces. The chip face in contact with the tool rake face has the highest temperature and then incurs a thermal expansion. The opposite face in contact with air has the lowest temperature and it is not affected by the thermal expansion. Consequently, this one-side expansion of the chip when formed induces the curling effect. When machining at low temperature, the thermal effect responsible for chip curling is significantly reduced. Furthermore, lowering the temperature makes the material stiffer which avoids the chip deformation when forming, especially the transversal deformation responsible for chip curling.

3.2. Microscopic cutting behavior of flax fibers inside UDF/PP composites

Fig. 5 illustrates the microscopic state of machined UDF/PP surfaces at each cutting condition. SEM images of Fig. 5 shows that flax fibers have an important effect on the microscopic surface integrity depending on their cutting behaviors. Indeed, cutting with negative rake angle induces a high rate of uncut fiber extremities that remain on machined surfaces following the cutting direction. This is a sign that the fiber shearing in this cutting configuration is not efficient. With negative rake angle, thermal effect is insignificant since both room and low temperatures induce almost the same cutting behavior (Fig. 5(a) and Fig. 5(e)). By increasing the rake angle from a negative value to zero, the uncut fiber extremities rate decreases and from the zero rake angle to positive values, the effect of the rake angle becomes insignificant while the thermal effect becomes more obvious. Indeed, when comparing the SEM images between room and low temperature from zero rake angles, it can be seen that the morphology of flax fibers is different. At room temperature, flax elementary fibers are deformed following the cutting direction. It is difficult to distinguish the elementary fibers cross-sections at room temperature cutting. At low temperature, flax elementary fibers show less deformation and their cross-sections are more obvious. The high transverse and cross-section deformations at room temperature modify the fibers shape and this gives the impression that room and low temperature SEM images are not at the same scale. It seems also that the fibers density is higher at low temperature cutting. This is due to the matrix deformation and its plastic flow on the machined surface which hide some fibers cross-sections.

SEM images show that cutting at low workpiece temperature increases the shearing efficiency of flax elementary fibers which decreases their plastic deformation and, then, reduces the uncut fiber

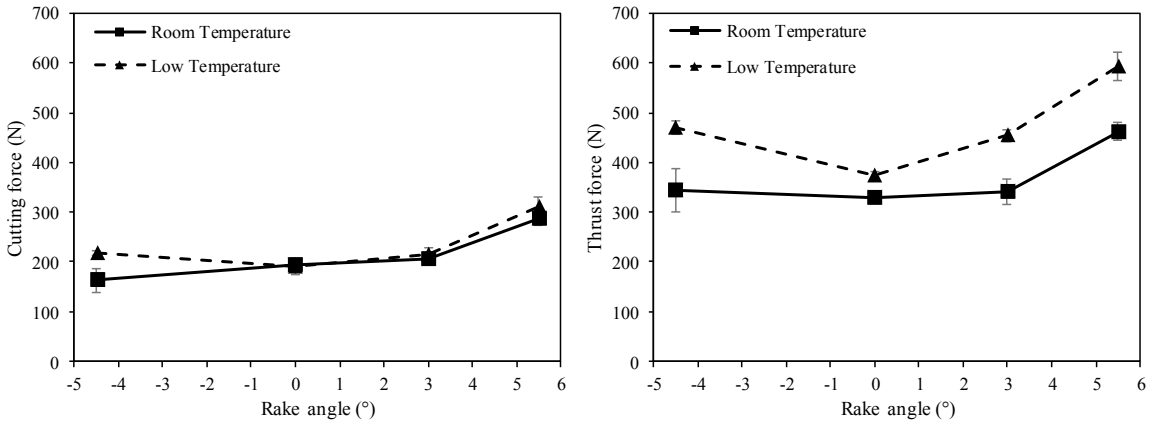

Fig. 6. Machining forces behaviors of UDF/PP at the different cutting conditions

extremities. This is the sign that the thermal effect is highly present in machining NFRP composites. Indeed, machining processes based on material removal induce high temperature at the shearing zone. Increasing the cutting contact temperature increases the material softening at the cutting zone and, then, its ability to deform. For UDF/PP composites used in this study, it is well known that PP matrix is a viscoelastic polymer with high elasticity and adhesion [28,29]. Moreover, it has been reported that flax fibers also show a viscoelastic behavior due to the non-cellulosic polymers and amorphous cellulose inside the elementary fiber structure [30]. This can explain the significant thermal effect when cutting UDF/PP composites because machining viscoelastic polymers is difficult at room temperature because of its softness, high elasticity and adhesion [31]. Therefore, lowering the polymer temperature when cutting increases its apparent rigidity and, then, improve the cutting contact stiffness.

Increasing the PP stiffness by cooling the sample temperature can also improve the fibers maintain during the cutting contact which makes the fibers shearing more efficient. Indeed, the glass transition temperature (T_g) of PP is around 0°C [32]. When the cutting temperature exceeds the T_g, degradation of resin will occur and the matrix cannot provide enough support to the fibers [33]. Therefore, lowering the sample temperature to be around the matrix T_g can avoid this issue.

3.3. Tribological cutting performance of UDF/PP composites

Fig. 6 presents the tribological forces induced by the cutting process. Globally, thrust forces are higher than cutting forces. This behavior is different from that of synthetic fiber composites [18,20]. Increasing the rake angle slightly increases the cutting force while cooling the workpiece seems to not affect the cutting force behavior. However, the thermal effect is more obvious on the thrust force where lowering the sample temperature significantly increases the thrust force when cutting. The rake angle effect on the thrust force is also more significant at the low temperature where the low values of thrust force are reached with zero rake angle. Varying the rake angle to either positive or negative values considerably increases the thrust force.

The fact that thrust forces are higher than cutting forces can be due to the cellular microstructure of natural flax fibers. Indeed, cellulosic microfibrils, that are the origin of fibers rigidity and strength, are oriented along the fiber axis [13]. The main mechanical properties are then concentrated on the longitudinal direction of flax fibers. Since the fibers are oriented perpendicularly to the cutting direction in this study, the main material strength to the machining operation is also perpendicular to the cutting direction which can explain the highest thrust forces regarding cutting forces.

The effect of rake angle is related to the cutting

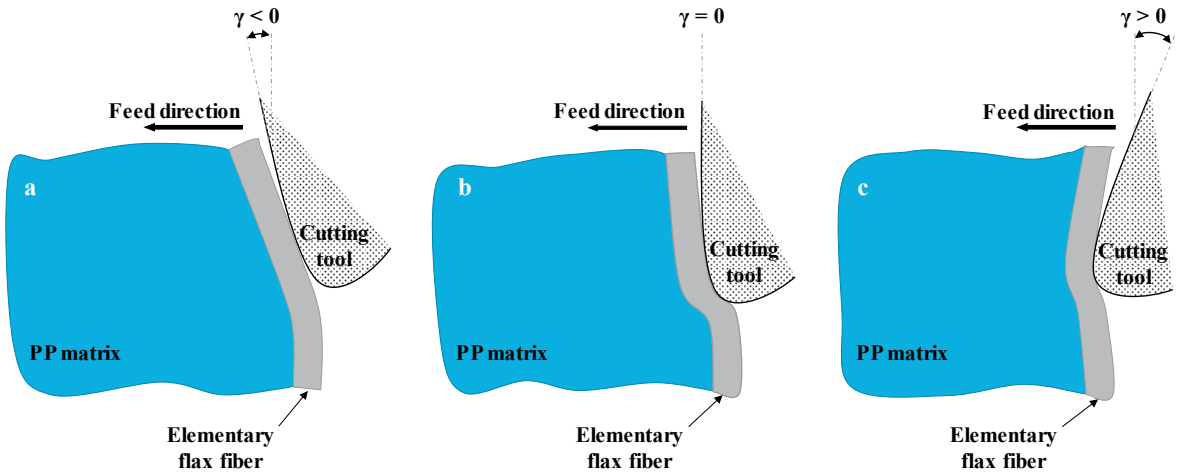

Fig. 7. Schematic depiction of flax fiber behavior under cutting contact (a) at negative rake angle, (b) at zero rake angle and (c) at positive rake angle

contact geometry performed between flax fibers and the rake face that defines how these elementary natural fibers are solicited as explained in Fig. 7. When the rake angle is negative, the rake face comes first into contact with fibers before the cutting edge (Fig. 7(a)). This configuration induces high fibers deformation in the cutting direction before shearing. This fibers deformation is more important over cutting natural fibers because of their high transversal flexibility [12]. During the contact with the cutting edge, the fibers will be partially stressed in the direction of microfibrils because of the previous transversal deformation. Then, the fibers strength increases which rises the machining forces.

When cutting with zero rake angle, rake face comes into contact with fibers at the same time as the cutting edge. Thus, flax fibers undergo a shear mechanism without high transversal deformation as illustrated in Fig. 7(b). In this cutting configuration, cellulosic microfibrils are less solicited in the fiber axis direction which decreases the machining forces.

When cutting with positive rake angle, the cutting edge comes first into contact with fibers before the rake face (Fig. 7(c)). This cutting configuration induces a mechanical stress on flax fibers similar to three-point bending. Thus, the cellulosic microfibrils are strongly solicited which increases the machining forces and increases also the cutting contact stiffness.

However, the tribological machining analysis of NFRP composites by rating the cutting force is not as revealing as that of synthetic fiber composites explained in section 1. Indeed, cutting force is among the main parameters that influences the surface quality of synthetic fiber composites and it is often used as an indicator of the machinability efficiency of these materials [33]. Nevertheless, this is not the case in this investigation for UDF/PP composites where the cutting force behavior in this section does not reflect the cutting behavior of fibers shown in section 3.2. This proves that only the cutting force cannot be used to qualify the machinability of NFRP composites.

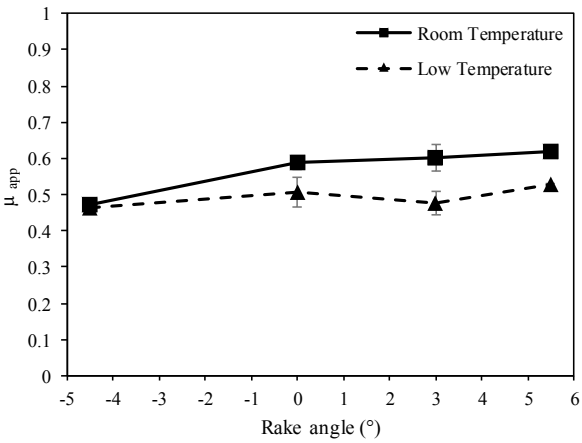

Fig. 8. Apparent cutting friction coefficient of UDF/PP at the different cutting conditions

Therefore, it is necessary to consider another tribological parameter that combines the effect of both cutting and thrust forces. Thus, the apparent cutting friction coefficient (μ_{app}) is calculated from the machining forces as the ratio between the cutting force (F_c) and thrust force (F_t) following the equation (1).

$$\mu_{app} = F_c/F_t \quad (1)$$

Fig. 8 shows the functional relationship between the cutting friction coefficient and the cutting behavior of flax fibers in Fig. 5. At the negative rake angle, there is no effect of lowering temperature on μ_{app}. From zero rake angle, μ_{app} is slightly increased and low temperature cutting induces less apparent friction than room temperature cutting. By comparing the apparent friction behavior and the cutting fibers behavior in section 3.2. It can be concluded that lowering the sample temperature increases the apparent material stiffness which avoid energy dissipation by friction (i.e. lowering μ_{app}). This increases the fibers shearing efficiency and improves the NFRP machinability. However, it is not the case when machining with negative rake angle because of the high fibers deformation which is due to the transversal flexibility of natural flax fibers.

3.4. Machining-induced surface roughness of UDF/PP composites

As mentioned in section 1, rating the surface roughness of NFRP machined surfaces requires the selection of relevant scales that can distinguish the effect of studied parameters. These relevant scales correspond the natural fibrous structure size inside the composite. For UDF/PP, the relevant scales are between the size of technical fibers (~50 µm) and the size of fiber yarns (~1 mm) [12]. Therefore, the optical objective resolution of the interferometer to calculate the mean arithmetic roughness (Sa) has

been chosen as 800×800 µm to fit with the pertinent scales of UDF/PP composites.

Fig. 9 confirms the tribological cutting behavior described in section 3.1 and section 3.2. negative rake angle induces the highest surface roughness where lowering the sample temperature is insignificant. From zero rake angle value, the machined surface roughness decreases and the thermal effect becomes significant where lowering the sample temperature reduces the surface roughness. Indeed, the machined NFRP surface roughness is intimately related to the natural fibers cutting behavior. When fibers shearing is not efficient, the cutting process induces more uncut fibers extremities on the machined surfaces which rises the irregularities on the surface topography and, then, increases the surface roughness [10–12].

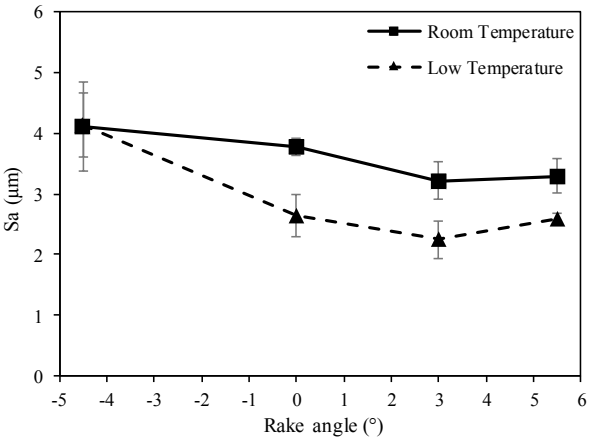

Fig. 9. Arithmetic machined surface roughness of UDF/PP at the different cutting conditions

4. Conclusions

Orthogonal cutting of UDF/PP has been performed under different tool rake angles and sample temperatures in order to investigate the thermal effect on the tribological cutting behavior of flax fibers within composites materials. The following conclusions can be drawn:

- The removed chip remains continuous under every cutting condition because of the high ductility induced by flax fibers and PP matrix. However, lowering the sample temperature reduces the chip curling.
- Lowering the sample temperature increases the apparent material stiffness which upgrades the flax fibers shearing and improves the machinability of UDF/PP composites.
- Cutting with the negative rake angle induces high flax fibers deformations during cutting contact which worsens the UDF/PP machinability. On the other hand, machining with small positive rake angles increases the cutting contact stiffness and improves the machinability of UDF/PP composites.
- Unlike synthetic fiber composites, cutting force is not a pertinent indicator of NFRP machinability. However, the apparent cutting friction effectively reveals the tribological cutting behavior of natural fibers inside composite materials.
- A poor flax fibers shearing is the main reason of increasing the machined surface roughness by increasing the uncut fibers extremities on the machined surface.

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