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5th CIRP CSI 2020

## Evolution of the surface integrity while turning a fillet radius in a martensitic stainless steel 15-5PH

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### Abstract

Surface integrity induced by longitudinal turning has been widely investigated in the literature. On the contrary, few works have aimed at investigating the surface integrity induced during turning of geometric singularities such as fillet radii. This paper investigates the surface integrity generated while turning a fillet radius in a martensitic stainless steel (15-5PH). The induced residual stresses, microstructure and mechanical properties have been characterized. Then, a geometrical analysis has revealed that the chip removal mechanisms vary continuously along the fillet radius, which, as a consequence, modify the cutting phenomena responsible of surface integrity modifications along the fillet radius. The study has highlighted that the microstructure remained stable but the residual stresses profiles differed especially regarding the compression peak intensity and the affected depth.

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*Keywords:* Fillet radii; Turning; Surface integrity

### 1. Introduction

Nowadays, mechanical industries have to ensure the durability of their engineering parts. Such complex parts are usually machined so as to create functional surfaces. Manufacturing processes generate modifications into these surfaces and as a consequence, play a major role on their life [1]. These induced-consequences - namely the modifications of microstructure, residual stress and topography of a material after processing - are often gathered in the concept of surface integrity. This work only deals with residual stresses and microstructure changes induced by the turning process.

In the past, most of studies have been dedicated to longitudinal turning [2-4]. However, investigation on geometrical singularities obtained by turning might be of

primary importance due to the geometrically-induced stress concentration that strongly influences the fatigue life during cyclic loadings [5].

This study focuses on fillet radius turning signature. After literature review, it seems that there is a lack of knowledge regarding fillet radius turning effects on surface integrity.

As a consequence, this paper aims at investigating the effect of such complex turning operation on surface integrity in a 15-5PH martensitic stainless steel. The first part deals with the presentation of the used materials and methods. The second part presents the main results. Eventually, a comparison is made between residual stress and microstructure evolutions along the fillet radius, giving some insight regarding the fatigue strength of such turned geometry.

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2. Material and methods

This paper lies in the framework of the finish turning of helicopter rotor mast fillet radii in 15-5PH martensitic stainless steel. One representative sample is machined (see dimensions in millimeters and cutting conditions on Fig. 1) with a CNC lathe. A new cutting edge is used for the finishing operation. It is worth to note that no tool wear is observed after machining. Three different zones are investigated: the longitudinal turning (1), the fillet radius turning (2) and the uphill face turning (3) (from the workpiece axis to the external surface).

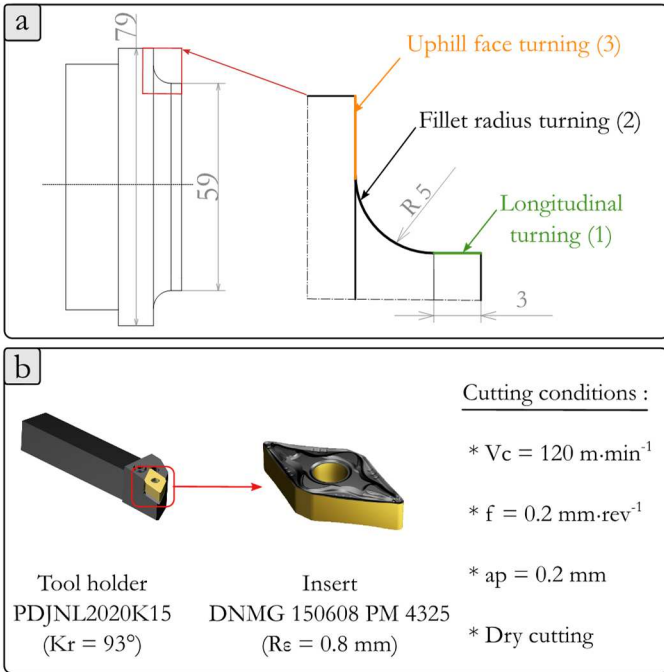


Fig. 1. The case-study a) workpiece geometry, b) cutting tool and conditions.

The 15-5PH is a martensitic stainless steel with structural hardening (Precipitation Hardening) whose chemical composition is given in Table 1. The tempering is achieved at 550°C and lasts 4 hours which leads to a hardness of 35 HRC. The optical micrography in Fig. 2 reveals, as expected, a martensitic microstructure based on needles with a size from few hundred nanometers to some micrometers.

Wire Electrical Discharge Machining is used to extract the specimen so as to make observations in the feed plane (XY). Samples are coated with a forty micron nickel layer to maintain the extreme surface unaffected during polishing. Specimen are mechanically polished with abrasive grains from grade 240 to grade 1200 and diamond suspensions from 3 microns to 0.05 microns which corresponds to a mix of colloidal silica and alumina.

Table 1. 15-5PH chemical composition in %wt.

C	Mn	Si	Cr	Ni	Cu	Nb	S	P	Fe
0.07	1	1	14	3.5	2.5	0.15	0.03	0.04	Bal.
Max.	Max.	Max.	15.5	5.5	4.5	0.45	Max.	Max.	.

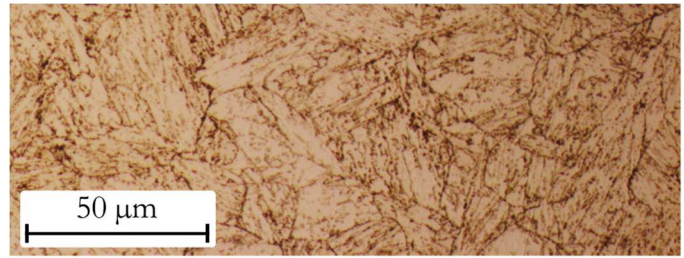


Fig. 2. 15-5PH bulk microstructure.

A Scanning Electron Microscope (back-scattering mode) is used to analyze the microstructure changes. Nanoindentation testing (Berkovich tip) is run to determine the turning-induced consequences in terms of mechanical properties [6]. More precisely, the CSM method (Continuous Stiffness Measurement) is used to measure continuously hardness as a function of the penetration depth which is experimentally set to 300 nanometers. Grids are performed and indents are spaced 3 times the total width of one indent to prevent interactions between the plastically deformed areas. The extracted values correspond to the average from 100 to 200 nanometers.

Turning-induced residual stresses are analysed using X-ray diffraction system with settings proposed by [7]. Two directions of analysis are considered: the axial direction is parallel to the workpiece axis and the circumferential one is perpendicular.

3. Results

The microstructure is refined beneath the machined surface (Fig. 3) over a size of about 2-3 microns. This Tribologically Transformed Layer (TTL) is composed of nanometric-sized grains, which is consistent with observations of [8]. It is worth to note that the TTL size does not much vary along the fillet radius (Fig. 4).

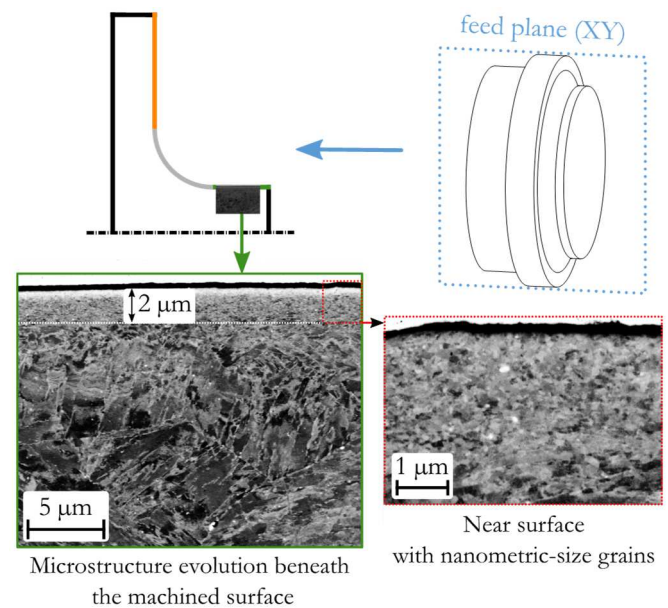


Fig. 3. SEM observation of microstructure changes beneath the surface in the feed plane (XY).

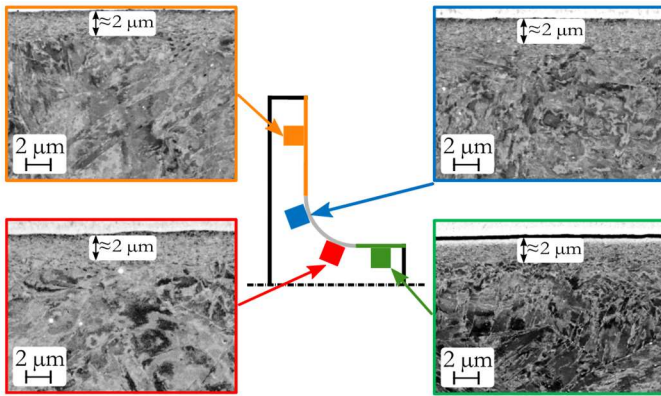


Fig. 4. Microstructure evolutions along the fillet radius.

In-depth mechanical properties reveals a 25% hardness increase in the TTL comparing to the bulk hardness (Fig. 5). This increase is likely due to a Hall-Petch effect. No variation in mechanical properties is observed beneath the TTL that is probably the consequence of the martensitic microstructure.

Note that the results correspond to the average of each line of the nanoindentation grid (6 indents per line), pointing out a quite low standard deviation about 0.1 GPa. Due to the small size of the TTL layer, it is not possible to evidence any variation of the hardness gradient along the fillet radius. Therefore, only one profile with the associated methodology is presented for the longitudinal turning region.

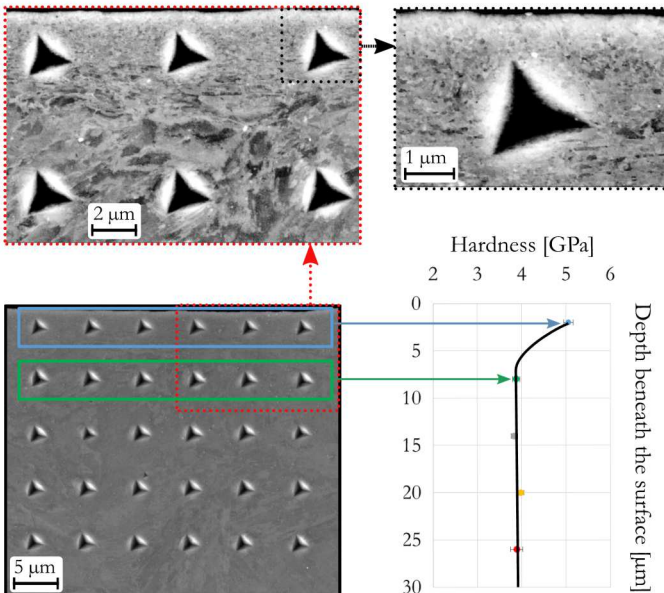


Fig. 5. Characterization of the hardness profile beneath the surface by nanoindentation in the longitudinal turning region.

For both turned zones, Fig. 6 highlights a typical hook-shape residual stresses profile that is commonly observed within turning operations. It starts with a tensile (or near-zero) surface stress and is followed by a compression peak. These

results are in good agreement with previous ones [9]. However, unlike microstructure evolution, the relative residual stress intensity differs between face turning and longitudinal turning. More precisely the compression peak and the affected depth are two times higher in the case of longitudinal turning.

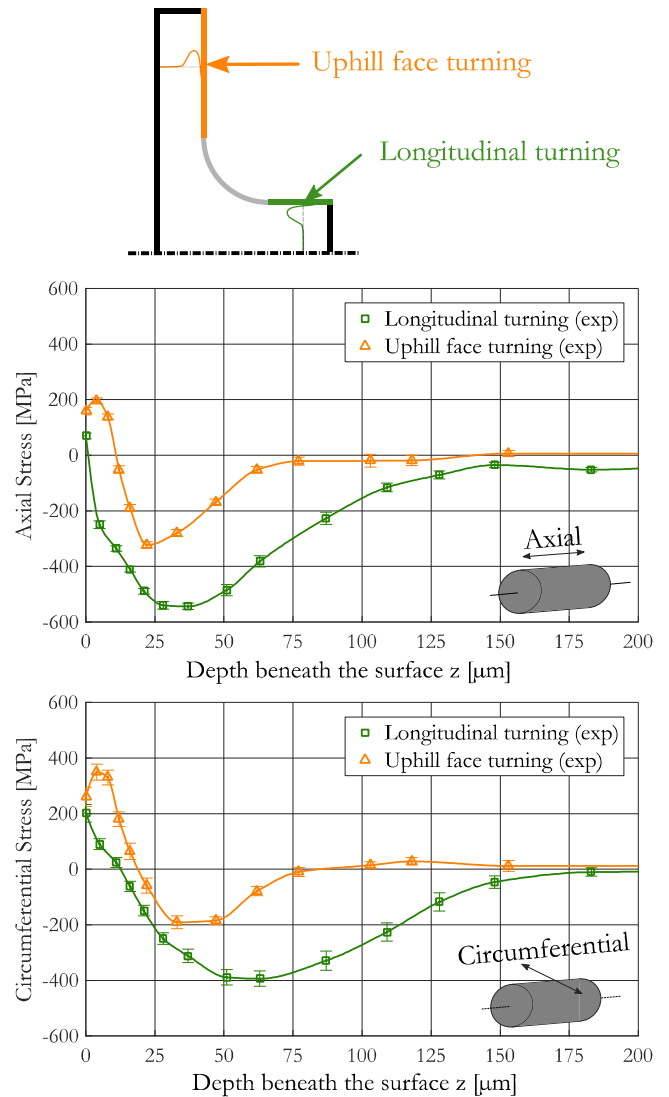


Fig.6. Comparison of residual stresses induced by longitudinal turning (square markers) and uphill face turning (triangle markers).

## 4. Discussion

### 4.1. Tribologically Transformed Layer (TTL)

The constant thickness of the turning-induced Tribologically Transformed Layer (TTL) along the fillet radius is likely due to the martensitic microstructure of the 15-5PH steel. The small needle size prevents significant dislocation hardening to be measurable using scanning electron microscopy and nanoindentation. The only microstructure evolution that can be noticed is the grain refinement process in the TTL induced by localized severe plastic deformation and that leads to a Hall-Petch like strengthening mechanism. This



remark is consistent with the investigations of [8-10] who reported similar TTL thicknesses on similar materials but using different turning conditions. [1] also observed no microstructure evolution when a surface mechanical treatments (roller-burnishing) is applied on a previously turned 15-5PH steel, highlighting again the weak sensitivity of TTL to contact loadings. Therefore investigating such turning-induced microstructure evolution in such material requires the knowledge of plastic flow and temperature at the scale of few microns. One can notice that [11] developed an eulerian-based method to understand friction-sliding induced microstructure evolution and pointed out huge temperature and plastic strain gradients in the very near-surface. This kind of methodology might be applied in the near-future to explain TTL formation after a turning operation.

4.2. Residual stresses

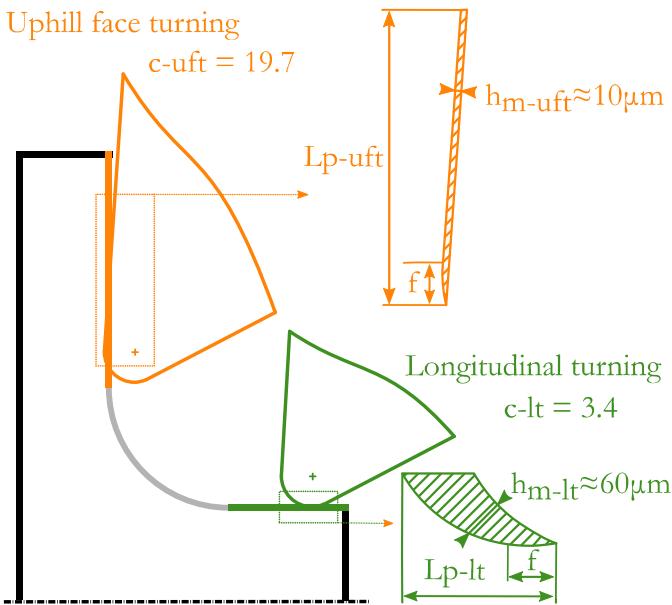


Fig.7. Different cutting regimes with different average uncut chip thicknesses  $h_m$  and coverage rates  $c$

Unlike microstructure evolution, it appears that the residual stress fields highly differ between face turning and longitudinal turning, even though the cutting conditions are similar.

The main difference between face turning and longitudinal turning is the cutting geometry as shown in Fig. 7. More precisely, a geometrical analysis reveals that the average uncut chip thickness ( $h_m$ ) strongly decreases from 60  $\mu\text{m}$  (longitudinal turning) to 10  $\mu\text{m}$  (uphill face turning) that is much lower than the cutting edge radius ( $R_\beta$ ) equal to 60  $\mu\text{m}$ . [13-14] highlighted that the contact radius ( $a$ ) (defined in equation 1) plays directly on the scratch-induced residual stress profiles. Indeed, the main conclusion of this work is the higher the contact radius, the higher the affected depth (see Fig. 8).

$$a = \sqrt{2h_m R_\beta - h_m^2} \tag{1}$$

Despite the difference between cutting and scratching, it can be assumed here (Fig. 6) that the decrease in residual stress intensity for face turning ( $a\text{-uft} = 33 \mu\text{m}$ ) contrary to longitudinal turning ( $a\text{-lt} = 60 \mu\text{m}$ ) may be a consequence of the decreasing contact radius. Moreover, the Fig.9 plots the two obtained residual stress profiles as a function of the ratio depth beneath the surface divided by the contact radius. As mentioned by [13], it is worth to note that the affected depth corresponds to 2-3 times the contact radius and the compression peak is located at 0.5-1 time de contact radius.

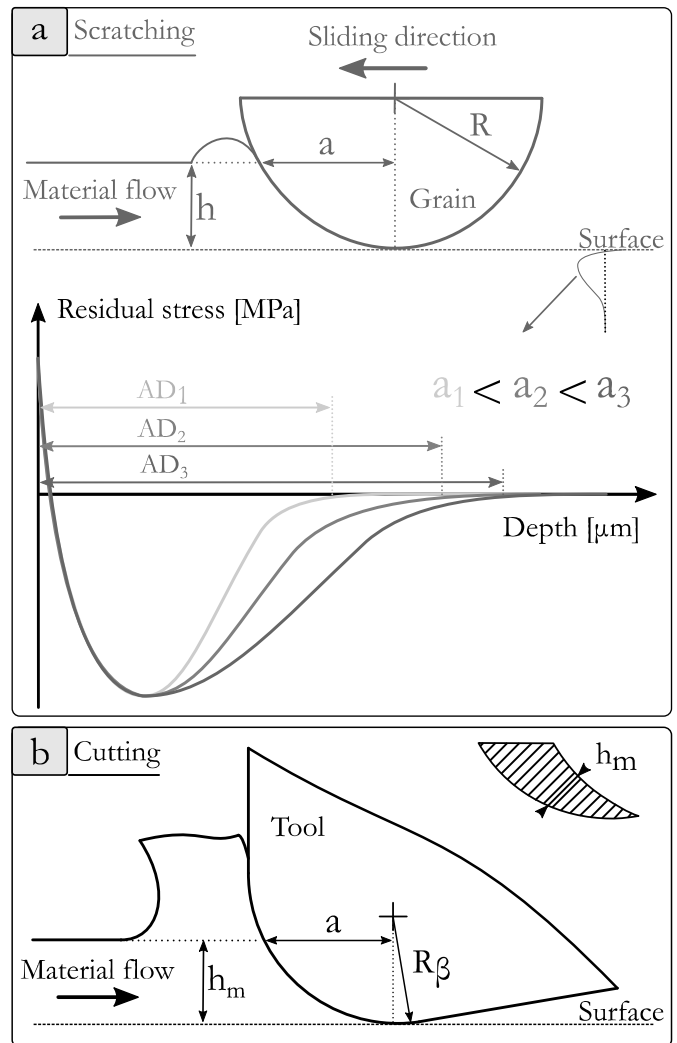


Fig.8. a) Influence of the contact radius ( $a$ ) on the affected depth ( $AD$ ) according to [13-14] while scratching b) similarity with cutting

Another explanation concerning the difference of the induced-residual stresses could be the coverage rate ( $c$ ) (defined in equation 2) where ( $L_p$ ) is the projected cutting edge in contact and ( $f$ ) the feed (see Fig. 7). Indeed, the coverage rate in longitudinal turning is almost 6 times higher than in the case of face turning. It means that the material in the case of uphill face turning is more subjected to cyclic loading.

Therefore, when applying such solicitations, the material response may be different due to the kinematic hardening phenomenon [15].

$$c = \frac{L_p}{f} \quad (2)$$

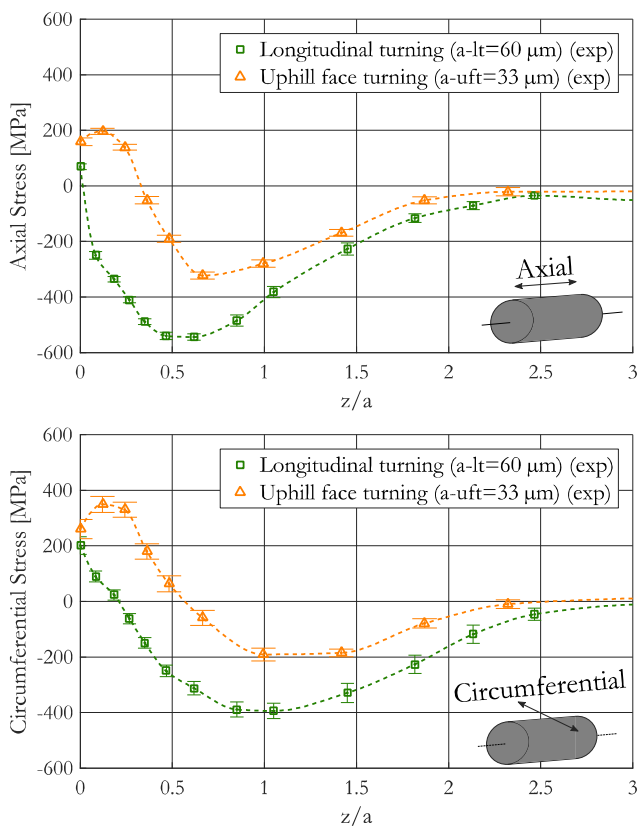
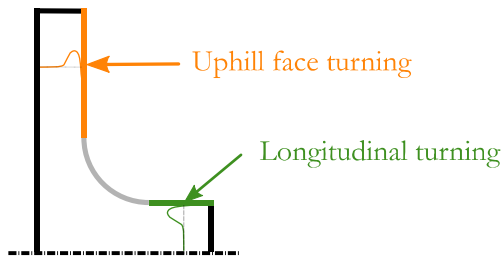


Fig.9. Relation between the contact radius and the residual stresses profiles induced by longitudinal turning and uphill face turning

#### 4.3. Microstructure modifications vs residual stresses

Microstructure modifications seem rather unaffected by local cutting conditions opposite the residual stresses fields. It is likely due to the fact that surface loading does not act in the same way regarding microstructure and residual stresses creation. Microstructure evolution is based on local severe plastic deformation and local temperature rise that can lead to grain refinement or dynamic recrystallization. Residual stresses is rather a consequence of plastic deformation incompatibilities and thus does not require severe plastic deformation. The weak effect on microstructure evolution is

probably due to the martensitic structure of the 15-5PH steel. One might wonder if the above conclusions would still hold on materials with a coarser microstructure. Future works will extend and refine the methodology developed in this paper to other kind of metals.

#### 4.4. Fatigue aspects

Regarding fatigue life in the framework of fillet radius, residual stress induced by uphill face turning should be rather detrimental to fatigue life than ones in longitudinal turning. Indeed, according to [16], the higher compression peak and the affected depth, the higher the fatigue strength, neglecting roughness and TTL effects.

### 5. Conclusions and perspectives

The main conclusions are:

- Microstructure refinement is limited to a depth of approximately 2 microns whatever the position in the fillet radius. The surface hardening (25%) concerns only the refined zone (Tribologically Transformed Layer) and is likely due to a grain boundary strengthening effect.
- Residual stress profiles strongly differ between longitudinal turning and uphill face turning. In such a case, the average uncut chip thickness much lower than the cutting edge radius leads to a small contact radius and may explain the lower residual stresses affected depth compared to longitudinal turning.
- Regarding residual stress profiles, uphill face turning should be more detrimental to fatigue life than longitudinal turning.

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