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Influence of a cutting fluid on the surface integrity and fatigue strength of 42CrMo4 drilled parts.

Rosalinda Solis[a,*], Raphaël Lorain[b] , Cici Mehmet[a], Thierry André[a], Hervé Pascal[a], Eliot Chaize[a], Emilie Viéville[a], Joël Rech[a]

[a] *Univ Lyon, Ecole Centrale de Lyon, CNRS, ENTPE, LTDS, UMR5513, ENISE, 42023 Saint Etienne, France*
[b] *TIVOLY, 50 rue de Molina, 42000 Saint-Etienne, France*

* Corresponding author. Tel.: +33-669-382-787; *E-mail address:* rosalinda.solis-garduno@enise.fr

Abstract

This study investigates the influence of a cutting fluid during the drilling operation on the surface integrity and fatigue strength of 42CrMo4 hardened steel. The investigation includes characterizing surface topography, microstructure at different hole locations, and residual stresses. Fatigue tests were conducted, and the results were correlated with observations on surface integrity. The findings reveal that crack initiation occurs in a transition zone within the hole, where the cutting process evolves from pure cutting to a region with a strongly adhesive layer. The absence of cutting fluid leads to increased surface roughness and tensile residual stresses, resulting in a 28% reduction in fatigue strength.

Keywords: Drilling ; Surface Integrity ; Fatigue ;

1. Introduction

In the context of carbon footprint reduction, the mechanical industry is striving to design lighter components while consuming fewer resources, particularly in terms of cutting fluid usage. To decrease the mass of mechanical parts, engineers must consider the impact of manufacturing processes on fatigue performance. Among these processes, machining processes are particularly critical as they are responsible for finishing functional surfaces. Fatigue performance is determined by several factors including roughness, residual stresses, and microstructure [1]. These three criteria are collectively referred to as surface integrity according to [2]. Numerous studies have demonstrated that machining processes alter surface integrity [3] and fatigue performance [4].

This article seeks to address an industrial demand from TIVOLY's clients (a drill manufacturing company), to optimize drilling operations in 42CrMo4 steels. As manufacturers aim for environmental effectiveness, the goal is to eliminate the use of cutting fluid in drilling operations without compromising the fatigue performance of the components.

Few studies have investigated the impact of drilling on surface integrity and gone as far as characterizing fatigue performance. Notable works include those of Kwong, who studied the influence of drilling process parameters on the subsurface damage and residual stress of Ni-based superalloy [5]. Bordin showed that the drill's cutting-edge preparation had an important effect on the surface integrity of the drilled holes [6]. Only Landon investigated the influence of drilling processes (axial drilling and orbital drilling) on both the surface integrity and fatigue strength of a 2024 T351 aluminum alloy. It was concluded that fatigue strength was mainly controlled by the depth of the strain hardened material layer [7].

Numerous studies have shown that cutting fluids have an important influence on surface integrity. For example, Hadad compared the performance of turning 42CrMo4 steel under

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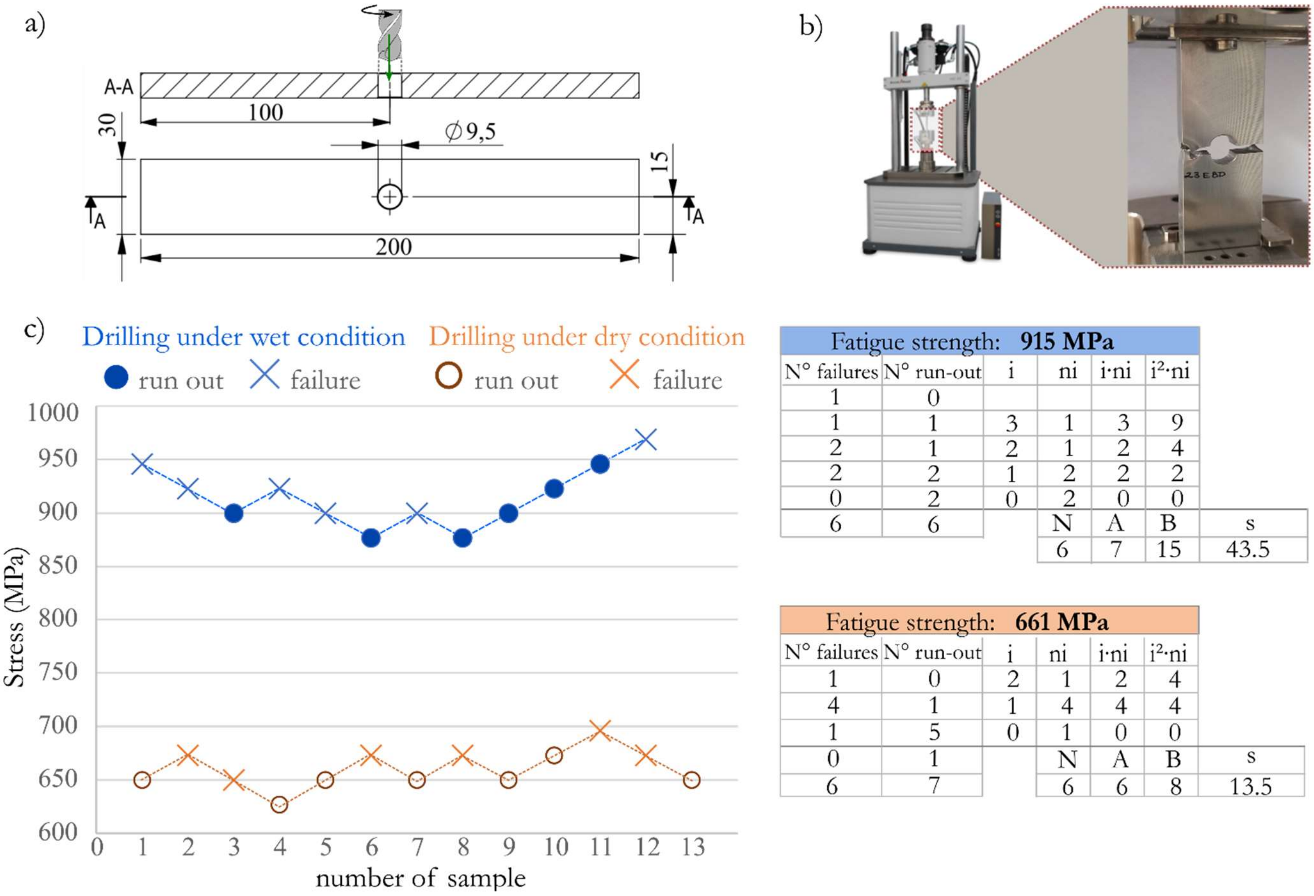

Fatigue strength: **915 MPa**						
N° failures	N° run-out	i	ni	i·ni	i²·ni	
1	0					
1	1	3	1	3	9	
2	1	2	1	2	4	
2	2	1	2	2	2	
0	2	0	2	0	0	
6	6		N	A	B	s
			6	7	15	43.5

Fatigue strength: **661 MPa**						
N° failures	N° run-out	i	ni	i·ni	i²·ni	
1	0	2	1	2	4	
4	1	1	4	4	4	
1	5	0	1	0	0	
0	1		N	A	B	s
6	7		6	6	8	13.5

Figure 1: (a) Fatigue T-Type specimen' geometry, adapted from the European Standard EN 6072:2010, $K_t = 2.35$, (b) Position of the sample in the fatigue machine, an example of a test that ended in part failure before reaching 1 million cycles (c) Fatigue test results following the staircase method for 1 million cycles

different lubricant conditions (dry wet and Minimum Quantity Lubrication MQL). His results showed that under wet and MQL conditions, surface roughness improved to a certain extent. Roughness was also influenced by the cutting parameters [8].

Concerning drilling surfaces, Girinon et al. showed that lubrication is a critical parameter on surface integrity. in drilling of 316L, 15-5 PH and Inconel 718 alloys. Dry drilling leaded to the development of tensile residual stress on the surface. Drilling under external and internal cooling generated compressive residual stresses and a limited affected layer [9]. There are considerably fewer articles that have explored the influence of cutting fluids on fatigue performance in drilling. For example, Sun et al. investigated the impact of conventional drilling and helical milling process under dry and wet conditions for: AL 2024-T3 and Ti 6Al-4V [10].

Therefore, it is apparent that the scientific literature has limited exploration regarding how cutting fluids impact the fatigue resistance of components during drilling. Thus, the aim of this paper is to investigate the properties of the drilled surface, considering both wet and dry conditions, and to assess their impact on the fatigue life of 42CrMo4 steel.

2. Materials and methods

2.1 Test specimen and material choice

For this study, 42CrMo4 (AISI 4140) martensitic low-alloy steel was used in its quenched and tempered state. It was acquired in the form of hot-rolled flat bars of the same chemical composition. Bar hardness is in the range of 310-320 HV. To relieve residual stresses, bars were heat treated to 400°C for 4 hours followed by a very low cooling rate.

From those bars, 40 axial fatigue specimens were manufactured. They had a section of 30 mm x 10 mm and a length of 200 mm (Fig. 1a). To exclusively explore the impact of the drilling operation, roughness and dimensional specifications were controlled throughout the machining process.

2.2 Drilling process

Axial drilling operations were conducted on a vertical CNC machining center. The cutting tool selected was a Tivoly® monobloc carbide drill SIRIUS III, diameter 9.5 mm, TiAIN coating. It has two internal channels for internal lubrication. The cooling lubricant is an 8% emulsion of Betronol EP V 1664-2 manufactured by MKU. The operation was made with the following conditions: cutting speed $v_c =$

100 m/min, axial feed $f = 0.2\ mm/rev$, drilling length *10 mm* throughout hole. 20 samples were drilled under simultaneous external and internal lubrication by a conventional flood technique. 20 samples were drilled without lubrication. After drilling, holes were chamfered at both extremities to remove burrs.

Applied forces and drilling torque were monitored with a piezoelectric dynamometer and a rotating dynamometer Kistler. To characterize the surface integrity generated after drilling, the cutting method proposed by Girinon *et al.* [11] was followed and it is presented in Fig. 2.

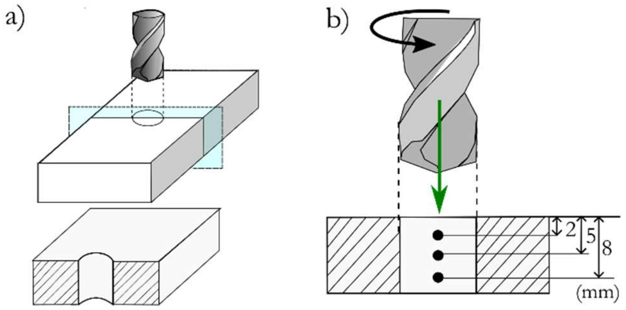

Figure 2: (a) sample cutting, (b) residual stress analysis (a) sample cutting, (b) residual stress analysis

The following surface integrity features have been studied because of their impact on the fatigue life of drilled parts:

- Surface roughness (parameter *Ra*)
- Microstructure
- Residual stress profiles

2.3 Surface Roughness assessment

Roughness 2D profiles were obtained along the depth of the drilled part with a Taylor-Hobson profilometer. Measurements were filtered using a Gaussian filter and a cut-off length of 0.8 mm. For each sample, three profiles were obtained to estimate the average result and the standard deviation.

2.4 *Microstructure assessment*

Following the drilling operation, samples were cut transversely under lubrication utilizing a cut-off wheel in aluminum oxide (Al_2O_3). Having a diameter of 305 mm, designed for hard ferrous metals. The operation was conducted at a rotational speed of 2750 rpm. Samples were subsequently hot mounted and polished, to facilitate observation of the drilling's cross-section (Fig. 3a). A metallographic attack was carried out on the polished sample by immersion in NITAL 4% to reveal the microstructure of the material.

2.5 Residual stress assessment

Axial and circumferential residual stresses were evaluated with X-ray diffractometry. First, three points were measured along the surface at 2 mm, 5 mm and 8 mm from the drill's entry (Fig. 2b). Secondly, to evaluate the affected depth from the drilling process, residual stresses were estimated in depth from the 5 mm point at the middle of the hole. Electrolytic polishing with saturated salt was used to gradually remove the outer layer of the specimen. This helped minimize any impact on the material's inherent stress state. This method was done successively in incremental steps of 30 µm until the residual stresses were inferior to 20 MPa. .

The diffraction conditions were: X-ray Tube Target: Cr, 20kV, 1 mA. Scanning time: 70s. Bragg angle: 156°. Plan {211}. Diameter of collimator diaphragm: 2mm.

2.6 Fatigue characterization

The fatigue limit for each condition was evaluated performing a staircase procedure, with a 23MPa step. The axial fatigue tests were performed on a servo-hydraulic testing machine with a 100 kN load cell. The tests were conducted at room temperature. Specimens were vertically clamped (Fig. 1b). A sinusoidal tensile-tensile load was applied in the longitudinal direction. A frequency of 10 Hz was adopted with a stress ratio of R = 0.05.

The staircase method was chosen for the assessment of fatigue strength after drilling. This method consists in determining the stress level to be applied to a specimen based on the outcome of the previous attempt, the fatigue endurance is estimated with a 50% failure probability [12].

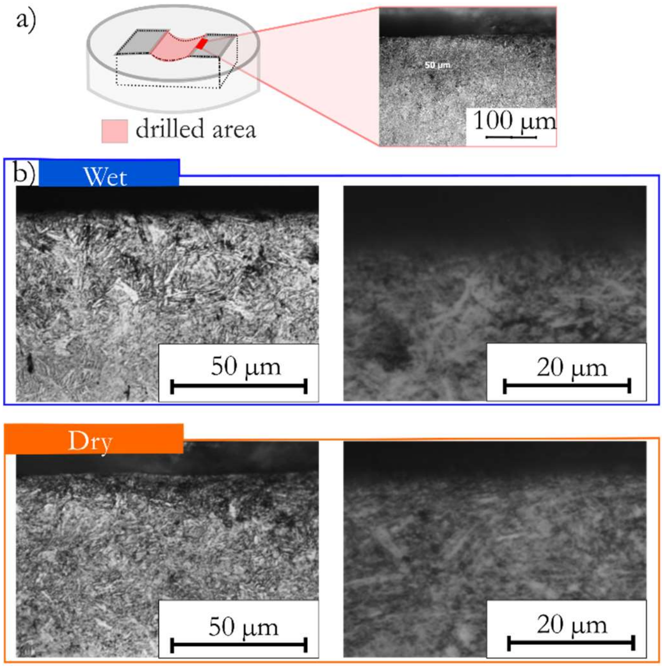

Figure 3 (a) sample mounting and an example of the observed surface, (b) micrographs after drilling for the 2 lubrication modes, no metallurgical variation or white layer was detected, microstructure remained martensitic

3. Results and discussion

3.1 Cutting forces during drilling operation

In Fig. 4, the evolution of thrust force and torque during drilling is depicted under both wet conditions (Fig. 4a) and dry conditions (Fig. 4c). For each curve, three distinct phases can be identified. The drill engagement stage is characterized by a rise in both thrust force and torque as the drill penetrates the material. In the second phase, when the drill is fully engaged, the forces stabilize since the chip thickness remains constant.

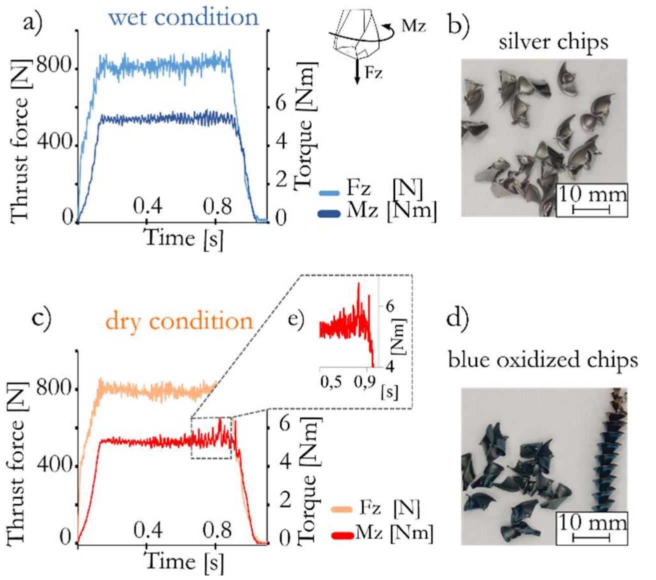

Figure 4: Evolution of thrust force and torque during drilling operations, (a) wet condition, (b) chips after drilling under wet conditions, (c) dry condition, (d) chips after drilling under wet conditions, (e) torque increase at the end of drilling

In dry drilling, there is a pronounced increase in torque towards the end (refer to Fig. 4e). This suggests difficulties in effectively evacuating chips. Accumulated chips contribute to heightened friction and cluster within the drill's flute, requiring additional force for the drill to rotate. However, the average thrust force does not exhibit an increase for either wet or dry conditions throughout the material removal phase.

Chip's colour is another noteworthy factor to consider. Under wet conditions (Fig. 4b) chips exhibited a conical shape and a silver colour. However, in dry drilling (Fig. 4d), chips became oxidized, indicating a significant increase in temperature at the cutting edge.

Temperature increasing and efforts can induce microstructural changes as well as metallurgical alterations. Therefore, microstructure was assessed after drilling operations. After microstructure revealing, no metallurgical variation or white layer was detected as seen in Fig. 3b. Microstructure remained martensitic.

3.2 Roughness profile evolution

The analysis of average surface roughness (refer to Fig. 5) shows that, at the drill's entry, roughness is three times higher in dry drilling compared to the case with lubrication (wet condition). Dry drilling results in more pronounced damage at the entry point than at the exit. The scratches observed in Fig. 5b are a consequence of friction and sticking between the drill's flute and the material. During dry drilling, the lack of lubrication causes the formation of continuous chips, which have the potential to scratch the machined surface. This not only clogs the drill's grooves but also increases torque, thereby adversely affecting surface finish and leading to higher roughness. Under wet conditions, average roughness consistently maintained values below 0.6 µm, indicating a favourable surface finish.

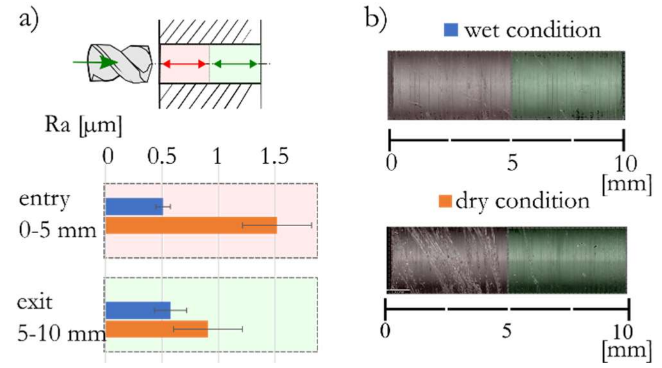

Figure 5 : (a) Roughness profile evolution under wet and dry condition, (b) topography generated after drilling under wet and dry conditions

3.3 Evolution of residual stresses on the drilled surface

Fig. 6 shows how surface residual stresses evolve under wet and dry conditions. Residual stress profiles shift from being compressive at the drill's entry (-200 MPa circumferential / -450 MPa axial), to becoming consistently tensile at the end (+200 MPa radial/ 0 MPa axial). One possible explanation is that as the drill penetrates, heat dissipation and chip evacuation become more challenging, creating temperature gradients and resulting in higher tensile residual stresses. The absence of metallurgical alterations (Fig. 3.b) suggests that residual stresses arise from plastic strain variances induced by thermal gradients, uncompensated by mechanical compressive load. Conversely, compressive stresses result from the drill's mechanical load. Under dry condition, residual stresses were exclusively tensile in the circumferential direction and increased from 100 MPa to 390 MPa (Fig. 6a). In the axial direction (Fig. 6b) residual stresses were compressive at the drill's entry (-200 MPa) but inferior in comparison to residual stress in the wet condition (-450 MPa). The residual stresses shifted gradually towards tensile and reached a peak value of 100 MPa.

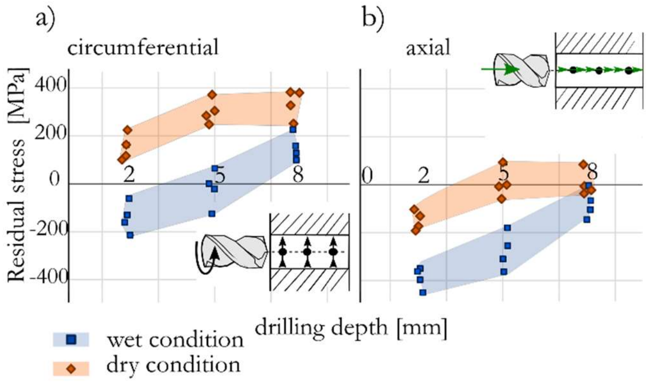

Figure 6: Experimental results of residual stresses on the external surface under wet and dry condition. (a) circumferential residual stresses, (b) axial residual stresses

A potential explanation is that the absence of cooling fluid impacted heat evacuation, resulting in a higher heat flux density and, consequently, the development of tensile residual stresses. It is noteworthy that the stress profile gap disappeared at the hole's exit, with residual stresses becoming tensile in the circumferential direction for both wet and dry conditions. One hypothesis is that the evolution of residual stress profiles corresponds to the passage of the cutting lips. The heat generated by the margins had an impact that could not be offset by the mechanical load of the drill.

3.4 Evolution of residual stresses in depth

Residual stresses were also estimated in depth at a midpoint within the hole (5 mm), for wet and dry conditions as shown in Fig. 7. In the circumferential direction (Fig. 7a), the affected layer had a depth of 50 µm, whereas in the axial direction (Fig. 7b) residual stresses extended to a deep of at least 150 µm.

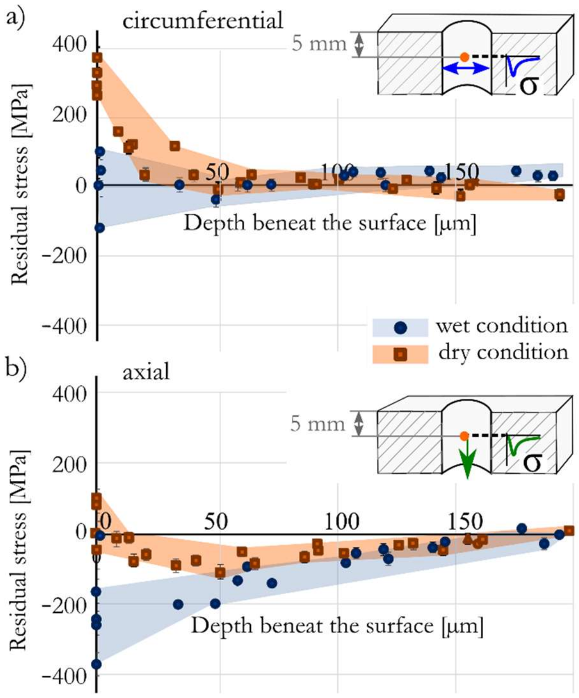

Figure 7 Evolution of residual stresses, (a) in the circumferential direction, (b) in the axial direction

In wet condition, residual stresses fluctuated between tensile and compressive stress, but their magnitude was lower in comparison to those in the dry condition at the hole's entry. The values were 300±50MPa (dry) and 0±100 MPa (wet) in the circumferential direction (Fig.7a), before rapidly diminishing toward zero after 50µm. In the axial direction (Fig. 7b), compressive stress was higher in wet conditions, reaching a peak of -300±100 MPa, as opposed to 0±50 MPa in dry conditions. Stresses rapidly decreased after 50µm and stabilize beyond 150µm.

Under dry conditions, thermal effects prominently contribute to the generation of tensile stresses at the hole's surface and within its depth. These tensile stresses hold the potential to impact fatigue life by fostering crack propagation. Conversely, under wet conditions, neutral (close to zero) residual stresses positively contribute to fatigue life, although there is uncertainty about whether the affected layer is sufficiently deep to influence overall fatigue life.

3.5 Fatigue test Results

Fig. 1c presents an overview of the loading history during the staircase campaign under both wet and dry conditions, providing the basis for estimating fatigue strength. The initial stress level was determined at 650 MPa from preliminary S-N data of heat treated 42CrMo4 steel [13]. The initial applied force was calculated based on the initial stress level and the stress concentration factor of open-hole samples (Kt =2,3).

For the dry condition, 13 samples were used. The minimum and maximum applied forces were: 55 kN – 61 kN. For the wet condition, 12 samples were used. The initial level started at 76 kN and the last level was 84 kN. The selected stress step size for this study is 23 MPa. Fatigue strength under wet conditions is determined to be $\sigma_{D\,wet(1M)} = 915 \pm 44$ MPa. Under dry conditions, it decreases to $\sigma_{D\,dry(1M)} = 661 \pm 14$ MPa, indicating a reduction of 254 MPa or a 28% loss in fatigue strength.

Observations were made on samples that failed the fatigue test to determine the location of crack initiation (Fig. 8). The results indicate that under wet conditions, crack initiation tended to occur in the middle of the hole, specifically between 4 mm to 5.5 mm from the entry (Fig. 8a.) Conversely, under dry conditions, crack initiation was slightly shifted upward, occurring between 3 mm and 4.5 mm from the entry. Upon comparing these results with the residual surface stress profiles in Fig. 8b, it becomes evident that residual stresses alone cannot serve as the sole parameter for determining fatigue resistance. Specifically, under wet conditions, cracks tend to manifest where residual stresses are compressive, progressively transitioning, rather than at the hole's end where residual stresses are tensile and unfavorable for fatigue life. Similarly, under dry conditions, fatigue crack initiation occurs at the hole's entry, where tensile stresses are not at their peak, but rather in the region with the highest average roughness, as depicted in Fig. 8a. From this, it can be affirmed that roughness significantly influences the fatigue life of drilled 42CrMo4 steel parts. One hypothesis is that the affected layer may not be deep enough or that residual compressive stresses may not be sufficiently high to delay crack initiation. Additionally, enhancing surface roughness alone has the potential to substantially improve the fatigue strength of dry-drilled holes.

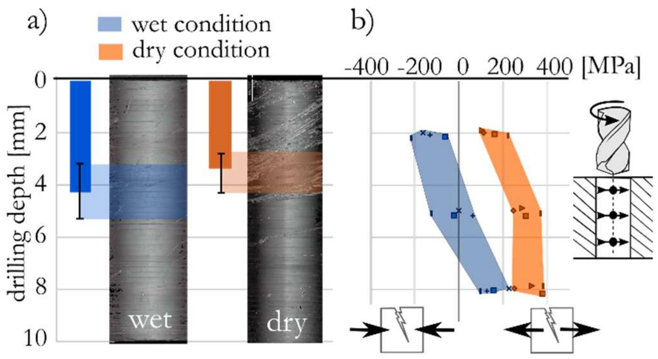

Figure 8 Average location of crack initiation, (a) influence of roughness, (b) influence of surface residual stresses

4. Conclusion

This study aimed to explore the impact of cutting fluid in the drilling process on 42CrMo4 quenched and tempered steel. Surface integrity was evaluated under both wet and dry conditions, and fatigue tests were conducted to establish a correlation between fatigue strength and surface integrity. The findings underscore the significant sensitivity of fatigue strength in drilled parts to the interaction of two crucial factors: surface roughness and residual stresses. Notably, the absence of lubrication results in increased surface roughness, creating areas susceptible to crack initiation. Additionally, it generates tensile residual stresses that further facilitate crack propagation. Surface roughness and residual stresses result as a consequence of the balance between thermal and mechanical influences during the drilling process. The results shown that, despite achieving satisfactory hole size under dry conditions, there was a 28% reduction in fatigue life. An improvement in the surface roughness may, therefore, play a main role in improving fatigue strength.

Currently, the factors influencing the fatigue strength of drilled components are articulated. In future works, it would be valuable to adopt a research approach similar to the one pioneered by Chomienne [14]. He introduced a strategy to discriminate the influence of various surface integrity features (including surface roughness, residual stress profiles, and microstructural state) on a material's fatigue resistance. This unique approach was already employed to assess the surface integrity features influencing the rotating bending fatigue of 15-5 PH martensitic stainless steel.

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