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# The Comparison of Effects of Liquid Carbon Dioxide and Conventional Flood Cooling on the Machining Conditions During Milling of Nickel-based Superalloys

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**Abstract**
In this scientific study, the authors have dealt with the slot milling of nickel-based superalloys. These alloys are among the most difficult materials to machine and are widely used in aerospace and energy industries. Due to the properties of the material, slot milling is a particular problem because tool wear happens quickly, and tool breakages are common. When these superalloys are machined, very high temperatures occur in the cutting zone, which cannot leave due to the extremely poor thermal conductivity of the material and will therefore transfer to the edges of the cutting tool, causing it to anneal, break off and fail. So, the researchers initiated a new field of research: cryogenically-assisted machining. In this paper, the authors used two cooling methods, the conventional flood cooling and cryogenic cooling with liquid carbon-dioxide ($LCO_2$). The effects of these cooling methods were tested focusing on the cutting forces, tool wear, chip morphology and surface roughness of the bottom of the slots. The aim was to determine the best cooling methods for these materials. Based on the results, it can be concluded that, $LCO_2$ has a negative effect on cutting forces, tool life and surface roughness. It only has a positive effect on chip formation. It can be see that, the lubricating effect has a greater impact on tool life, tool load and surface roughness of the milled slots than cooling.

**Keywords**
nickel-based superalloys, cryogenic machining, $LCO_2$, slot milling, tool wear, chip morphology

## 1 Introduction

Nickel-based superalloys are utilized in many applications, most notably in the aerospace and energy industries, which are constantly evolving [1, 2]. Furthermore, as electric cars are gaining ground in public transport, battery cell interconnection is becoming increasingly important in battery manufacturing [3]. According to a study, the aerospace industry's production volume will reach pre-Covid-19 level in 2023 and exceed it in 2024 [4]. This economic trend makes it even more urgent to study the machinability of these materials. In these fields, gas turbines, which are mainly made from different types of nickel and titan-based superalloys [5], are widely used. These superalloys are manufactured by turning [6], milling [7] and Wiper Grinding [8]. The parts of these turbines contain many slots, which can only be made by milling. On the bases of factory experience, milling of slots causes the most problems. Slot cutters wear very intensively, break often and the productivity of them is very low [9]. A further problem is that the edges of the slots are deburring, which is very difficult to remove [10]. In their work, Kaya and Akyüz [11] described the types of tool wear and the factors influencing the extent of tool wear in nickel-based superalloys. It was found that tool wear increases exponentially with escalating cutting temperature and force [11]. Thellaputta et al. [12] studied the effects of parameters on the machining process. According to their claim, the recommended cutting speeds range from 10 to 30 m/min when machining nickel-based superalloys with cemented carbide tools, because they could not endure the extreme temperatures resulting from high cutting speeds [12].

These materials are composed of two main phases: Gamma ($\gamma$) and Gamma-prime ($\gamma'$) solution [13]. Both phases have an FCC (Face Centred Cubic) lattice structure, where in the $\gamma$-phase the Ni and Al atoms are disordered in the lattice. In the $\gamma'$-phase the Ni atoms are located at the centre of the sheet and Al atoms at the peeks [14, 15]. Their lattice structure is shown in Fig. 1.

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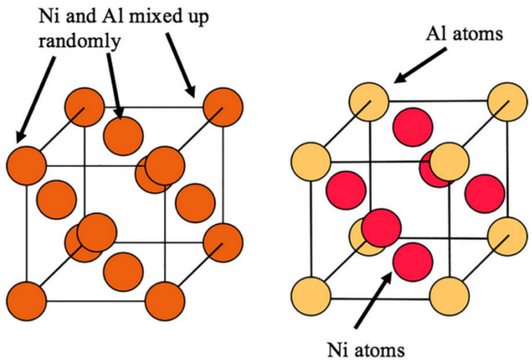



**Fig. 1** The lattice structure of $\gamma$ (left) and $\gamma'$ (right) phases, adapted from [13]

The nickel-based superalloys, which contain the $\gamma'$-phase of $Ni_3$ (Ti, Al) could retain their strength at very high temperatures, while other metal alloys could not. Basically, in the $\gamma$ and $\gamma'$ phases, the dislocations appear on the {111}-plane, however, the energy of the phase boundary in the {100}-plane decreases with increasing temperature, so the dislocations in the $\gamma'$ phase can move in these directions. This increases the strength as the dislocations are blocked through the {111} and {100} planes in the fabric structure. This is the result of the low plastic deformation capacity of the material. The machining process usually produces sheared chips [15–17]. Because of this dislocation mechanism, there is no tendency for these superalloys to lose strength with increasing temperature like other types of alloys, as shown in Fig. 2 [18]. This mechanism makes the machining process exceptionally difficult because the strength of these materials only starts to decrease at very high temperatures, which creates significant cutting forces and temperatures. They also have a very low thermal conductivity, which means that most of the heat is at the edges of the cutting tool.

Cryogenics is the production of physical phenomena at very low temperatures. Cryogenic temperatures, depending on the medium used, are between −273 °C and −30 °C,

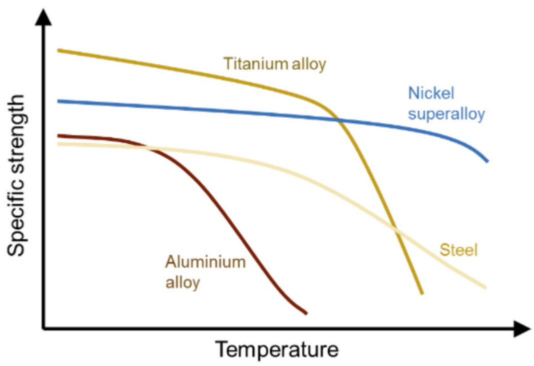



**Fig. 2** Specific strength as a function of temperature in the case of various metals [18]

which is lower than the temperatures encountered in ordinary processes. Such low temperatures also affect the properties of materials, including thermal conductivity, electrical resistance, ductility and strength [19].

Cryogenic cooling technology is used in many areas of life, such as the medical [20], automotive [21] and aerospace [22] industry. The major problems are the machining of superalloys and the tool steels which are used in these industries, which is why cryogenic technology is used both in the preparation of cutting tools to increase tool life, and directly in the cutting technology to reduce the temperature in the cutting zone [23]. Aramcharoen et al. [24] and also Jebaraj et al. [25] have reported in their research, that if the machining temperature is greatly reduced, it improves the friction between the workpiece and the tool, reduces the amount of cutting force and tool wear, improves chip breaking and the quality of the machined surface [24, 25]. Ravi and Kumar [26] investigated the dry, wet and liquid nitrogen cooling during the machining of hardened AISI H13 tool steel. Based on the results they stated the machining with $LN_2$ provides lower cutting temperature, tool wear, surface roughness and cutting force compared to those under dry, wet machining conditions. This is because of the better cooling and lubrication effect through substantial reduction in the cutting zone temperature. The reduction in the cutting temperature using the $LN_2$ coolant is substantial at lower cutting speeds [26].

Because of these advantages, the flood and cryogen cooling method with $LCO_2$ were tested on GTD-111 nickel-based superalloys. The authors measured the cutting forces, tool wear, the surface roughness on the bottom of the slots, and the chip formation. The goal was to determine the superior cooling method.

## 2 The experimental environment

In Section 2.1, the design of the experiment will be presented. The experimental set-up on which the milling experiments were carried out is presented, that includes the machine tool, the cryogenic cooling system of our own design, the force dynamometer, the cutting tool, and the tool holder. Furthermore, the technological parameters and the tool path used are presented.

### 2.1 The experimental setup

The hard milling can cause extreme stress for a machining center, so a robust and highly rigid one is required, therefore the NCT EmL-850D was chosen. The experimental setup is shown in Fig. 3.

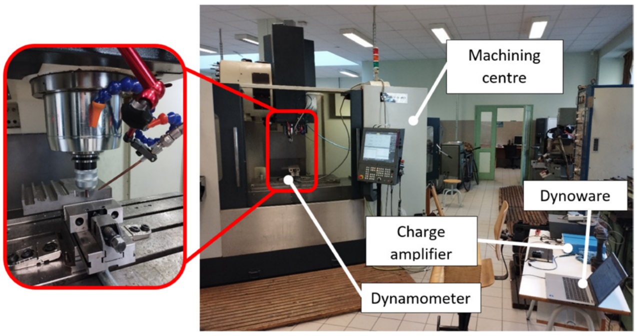



**Fig. 3** Experimental setup

The authors used a KISTLER 9257B type of dynamometer with a KISTLER 5007 type of analogue charge amplifier unit to measure $F_x$, $F_y$ and $F_z$ components of cutting forces in Descartes' coordinate system. Results were recorded using the DynoWare software and the original signal evaluated using the OriginPro 2021 software. Since the force signal was very noisy due to the high vibration, it needed to be filtered. For this purpose, the Reduce by Group function was used, which filters the original signal for the entire signal interval.

To carry out the experiments, the authors have built a cryogenic cooling system of their own design, which allowed them to inject liquid carbon dioxide into the cutting zone. The immersion tube bottle was chosen because it allows the extraction of $LCO_2$ from the bottom of the cylinder at a −78 °C. The cylinder contained 30 kg of charge at a pressure of 57 bars. A pressure reducer was not used because at lower pressures the medium becomes gaseous at room temperature. This gas medium would already have a much higher temperature, which would not be sufficient to cool the cutting zone.

The authors chose a flexible, stainless-steel hose to connect the cylinder to the nozzle because it can withstand both very low temperatures and pressures up to 57 bar, and it provides a flexible connection. For the nozzle, a bendable oxyacetylene burner nozzle was chosen because it can be easily adjusted to the tool and it has the necessary hole diameter. The schematic diagram of cryogenic cooling system is shown in Fig. 4.

## 2.2 Material

In this research, the authors used a GTD-111 nickel-based superalloy as the workpiece material. Chemical composition, mechanical and physical properties are shown in Tables 1 to 3.

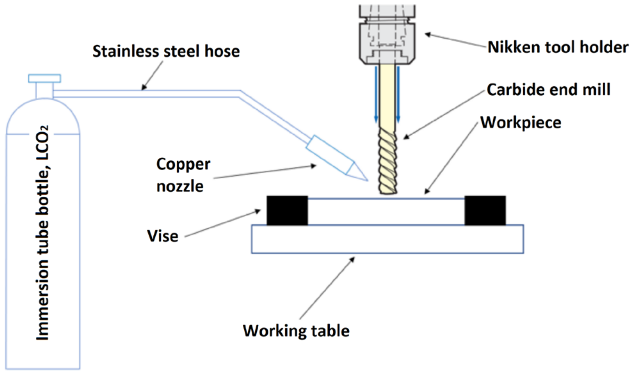



**Fig. 4** Schematic diagram of cryogenic cooling system with $LCO_2$ coolant

**Table 1** Chemical composition of GTD-111

| Ni (%) | C (%) | Cr (%) | Co (%) | Al (%) | Ti (%) | W (%) | Mo (%) | Ta (%) | B (%) |
|---|---|---|---|---|---|---|---|---|---|
| 62.37 | 0.06 | 13.7 | 9.0 | 2.8 | 4.7 | 3.5 | 1.4 | 2.4 | 0.05 |

**Table 2** Mechanical properties of GTD-111

| Tensile strength ($R_m$ (MPa)) | Stretch ($A_5$ (%)) | Contraction ($Z$ (%)) | Hardness (HRC) |
|---|---|---|---|
| 1310 | 8 | 5 | 41.4 |

**Table 3** Physical properties of GTD-111

| Density ($\rho$ (kg/m$^3$)) | Thermal conductivity on 20 °C (λ (W/m·K)) | Specific heat on 20 °C ($c$ (J/ kg K)) |
|---|---|---|
| 8000 | 12.56 | 0.452 × 103 |

## 2.3 Cutting tool and tool holder

For slot milling, BZL5D080R05L064S18P solid carbide end millers were used. The tools had a diameter of 8 mm and 5 edges [27]. The authors used Nikken multilock milling chuck types of tool holders, because a high clamping force is needed, and this one can generate 3–4 times the clamping force of conventional collet chuck tool holder. The tool before and tool after machining with $LCO_2$ coolant are shown in Fig. 5.

## 2.4 Applied cutting data, trochoidal strategy and cooling methods

The applied technological parameters for the experiments are based on the tool catalogue (cutting speed was $v_c$ = 28 m/min, feed per tooth was $f_z$ = 0.01 mm/tooth, axial depth of the cut was $a_p$ = 10 mm, and the radial depth of the cut was $a_e$ = 0.8 mm). Toolpaths also have a big influence on the forces loading on the tool and the roughness of the machined slots [28]. Kovács et al. studied the effects of toolpaths on surface roughness and found

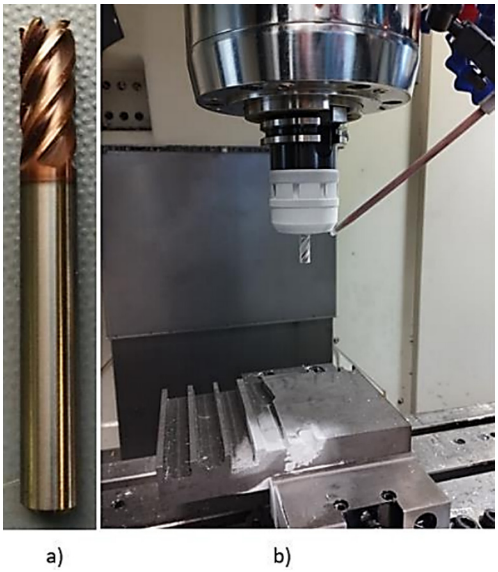



**Fig. 5** a) Cutting tool before and b) cutting tool after cryogenic machining

that the Adaptive strategy produced the best results [29]. Therefore, the authors have chosen Jacso's trochoidal strategy [30], which is very similar to the Adaptive strategy, because it keeps the contact angle constant during of the whole machining, thus reducing the dynamic stresses on the tool, which is particularly important when milling such materials. The tool path is shown in Fig. 6. Each slot size was 12 mm in length, 12 mm in width and 10 mm in depth.

During the machining process, a MOL Emolin 120 type biostable coolant was used for flood cooling mixed with water at a concentration of 5%. In the case of cooling with liquid carbon dioxide, the mass flow rate was 0.7 kg/min in the liquid phase.

## 3 Results

In Section 3, the machining force components measured during milling experiments, tool wear, removed chips during machining, surface roughness and widths of machined slots, and sorting are presented.

### 3.1 Cutting forces

The $F_x$, $F_y$ and $F_z$ component of cutting forces as they were measured during the machining with the flood and $LCO_2$ coolant are shown in Figs. 7 to 9.

In general, Figs. 7 and 8. show that the tendencies of the forces acting are the same. In the case of $LCO_2$ cooling, lower cutting forces were measured up to the middle of the slot, but from this point onward, the increase in cutting forces continued at a similar slope, reaching higher values than in the case of flood cooling. With regards to flood cooling,

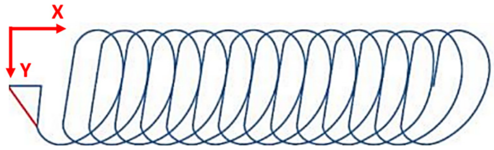



**Fig. 6** Applied toolpath

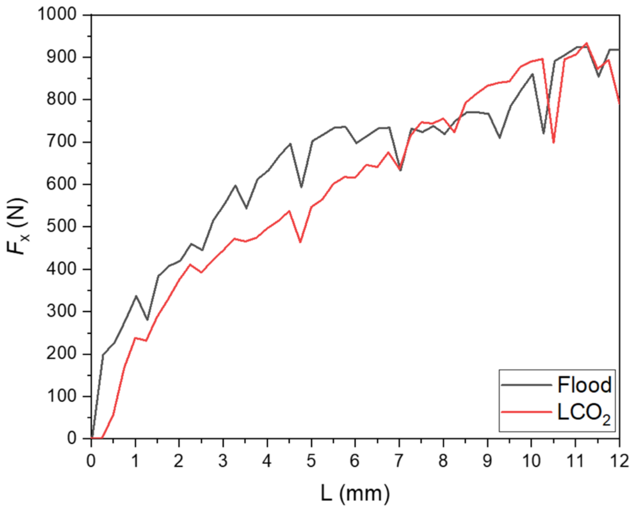



**Fig. 7** $F_x$ component of cutting force as a function of the length of the machined slot

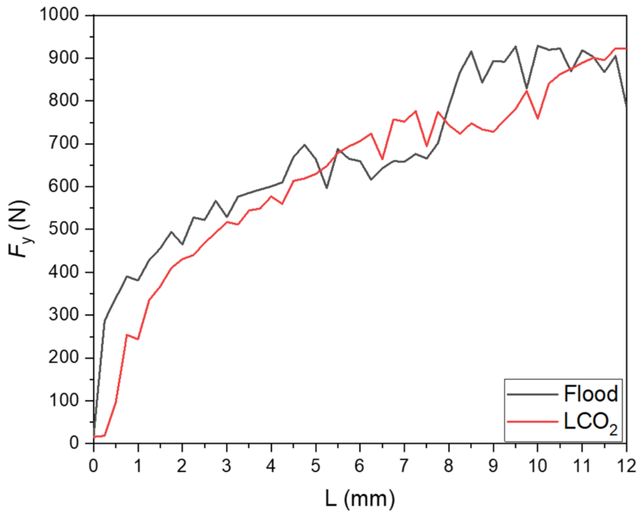



**Fig. 8** $F_y$ component of cutting force as a function of the length of the machined slot

the force components initially increased at a higher rate until the edge wore in, which occurred in the middle of the slot. From this point, the increase stagnated up to a machining length of 9 mm and then started to increase again, but with a smaller trend than in the case of $LCO_2$ cooling. There is not much difference between the maximum values, which would have required a longer machining length.

For the $F_z$ force component, the trends observed for the $F_x$ and $F_y$ force components are the same, but the directions of the force components are different for the two

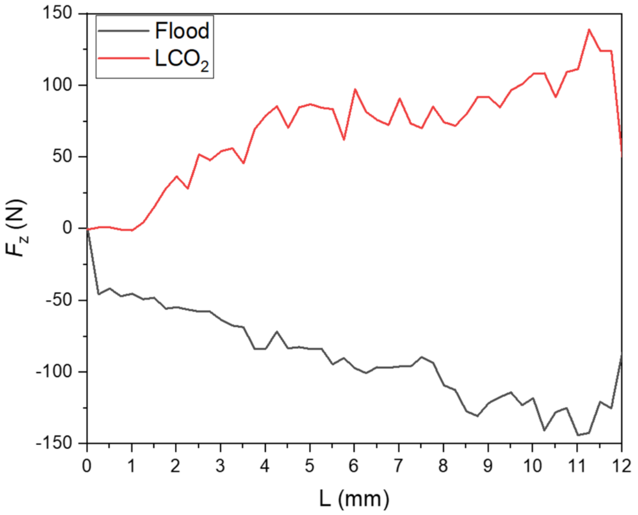



**Fig. 9** $F_z$ component of cutting force as a function of the length of the machined slot

cooling methods. A positive force component was measured for cryogenic cooling and a negative force component for flood cooling. This suggests that the cooling caused the material to become brittle, so greater forming forces were required during the cutting process and the tool wanted to tear the workpiece out of the vice. The procedure of force measurement is same in case of 2 measurements, only a cooling-lubricating method was changed.

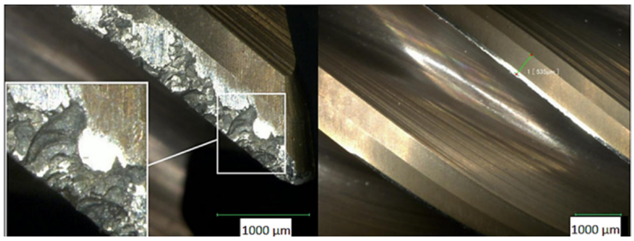
A positive $F_z$ force component was observed for $LCO_2$ cooling, where the cooling effect was significant. For flood cooling, where the lubricating effect prevailed, a negative $F_z$ force component was observed. Combining the two cooling methods could lead to outstanding results.

### 3.2 Tool wear

Microscopic images of the tools after machining are shown in Fig. 10. Tool edges used in cryogenic cooling are detached and minimal edge deposits are observed. The main edge is essentially worn out. In contrast, the tool used for flood cooling only shows wear from use. Hence it can be concluded that lubrication plays a critical role in machining, the dry ice generated during cooling by itself, and the cooling is not sufficient.

### 3.3 Chip morphology

The chips obtained by the 2 cooling methods are shown in Figs. 11 and 12. As shown in Figs. 11 and 12. milling with $LCO_2$ cooling produced significantly smaller and brighter chips than utilizing flood cooling. This is due to the brittleness of the raw material. These small chips are better for slot milling because they can leave the cutting zone more easily, avoiding re-chipping and jamming between the




a) b)

**Fig. 10** Used tool in a) $LCO_2$ cooling; b) flood cooling

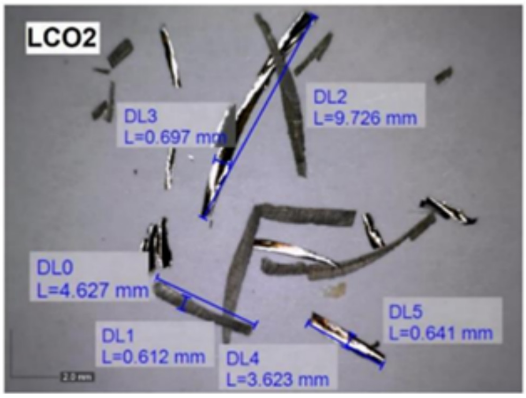



**Fig. 11** Chips from milling experiment with $LCO_2$

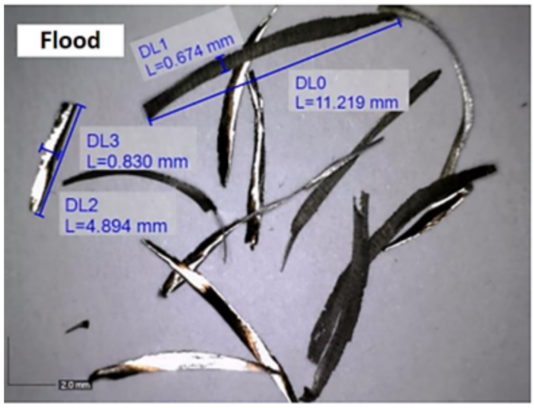



**Fig. 12** Chips from milling experiment with flood cooling

cutting tool and the workpiece. Furthermore, the cutting tools do not require chip breaker slots to break the chips.

### 3.4 Surface roughness

The surface roughness values obtained for each cooling method are shown in Fig. 13. The surface roughness of each slot was measured 3 times with a Mitutoyo Formtracer SV-3100 tactile roughness tester, then the results were averaged, and these values were plotted with the standard deviation.

As shown in Fig. 13., the wet cooling resulted in twice the surface quality of $LCO_2$ cooling. This is due to the brittleness of the material and the lack of lubrication.

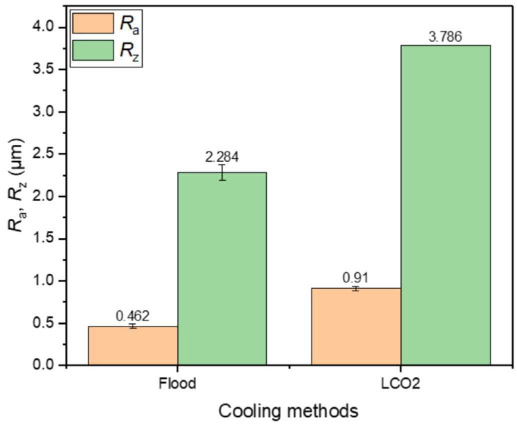



**Fig. 13** The average surface roughness and main roughness depth achieved for each cooling methods

The trend in surface roughness is the same as of the tool wear shown in Fig. 10. It can be observed that lubrication plays a significant role in the machining process.

## 4 Conclusions

The aim of this paper was to investigate the effects of cooling methods on the cutting forces, the tool wear, the chips and the surface quality of the bottom of the slot. The authors state the following conclusions:

- The cooling methods have a great influence on the applied cutting forces, as shown in Figs. 7 to 9.
- Lubrication is fundamentally more important in machining than cooling, as shown in the tools in Fig. 10.
- Cooling significantly improved the chip formation process, as it resulted in fragmented chips, as shown in Figs. 11 and 12.
- Lubrication also has a substantial impact on the quality of the machined surfaces in positive direction, as shown in Fig. 13.

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