Effects of channel contour laser strategies on fatigue properties and residual stresses of laser powder bed printed maraging steel

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Abstract
Laser powder bed fusion is widely used for tooling applications, such as mould insert: conformal cooling channels are designed to decrease cycling time and homogenize the cooling rate. The Achilles’ heel of additive manufacturing mould is the cooling channels close to the surface which generate high stress concentration and are not machined; as a result, they create weaknesses in the part and are likely to reduce the lifespan of the mould. It is necessary to study the impact of such channels on properties (fatigue, residual stresses, microstructure) and determine optimized laser strategies to reduce porosity that may occur near a contour. Residual stresses were first estimated above an internal channel after different heat treatments, and fatigue specimens were printed with a 3-mm diameter channel on an EOS M270 printer using different strategies such as several contours with a concentric offset. The impact of these strategies on fatigue properties was analysed through microstructural observations. Here, it was found that a double contour with an offset improved the fatigue life of the part by more than 10 times compared to the standard single contour strategy.

Keywords Additive manufacturing · Conformal cooling · Tools · Laser powder bed fusion

1 Introduction
The tooling sector is already a flagship for the additive manufacturing (AM) sector: AM is a well-established solution to design complex cooling channels as it offers more freedom than machining. In injection moulding or in die casting [1], the surface quality of the product and the cycling time are directly linked to the heat transfer between the injected mass and the mould [2, 3]. To control and homogenize the temperature of the insert, cooling channels are introduced (cf. Fig. 1). Traditionally, these channels are obtained by drilling after the machining of the mould insert. The cooling channels manufactured through AM are able to map the moulding surface, while the one obtained through drilling are not always able to reach the vicinity of the moulding surface. As a result, the quality of the product parts is significantly improved, and the cycling time is reduced. This is of particular interest when considering complex moulding surfaces which cannot be reached by drilling. As these channels are mapping the mould surface, the technology is usually referred to as “conformal cooling.”

Metal AM technologies also offers the possibility of building hybrid moulds [4–6], where an additively manufactured portion of the insert is built over of a prefabricated mould block. This means that only the parts where AM is required are manufactured using laser powder bed fusion (LPBF) [7], saving money by reducing the expensive manufacturing time (cf. Fig. 1). Maraging 300 (X2NiCoMo18-9-5) is the alloy widely used for this application [8, 9] because of its high ductility before heat treatment, its high strength, good hardness [10], and dimensional stability during aging [11] even though stainless grades are also available for this application [12–14]. LPBF remains most widely used technology for this application even though direct energy deposition has also been used [15–17].

Achilles’ heel of AM tools with conformal cooling channels is the channel contours: indeed, they generate high stress concentration during the tool life. This is particularly critical since these channels are as close as possible to the
moulding surface. Since they are not machined and therefore have a high roughness (cf. Fig. 2), they are also likely to induce cracks opening which might impact the fatigue performance of the tool [19]. Several studies in AM on fatigue properties are dealing with machined or polished samples [20] and thus are not relevant to predict the behaviour of such channels: to assess the fatigue performances, it is relevant to also study the effect of as built internal channels on the material behaviour.

Roughness is a well-known key point and one of the important issues in the AM process, and it is particularly hard to improve it, especially in the roof of complex internal channels. While all the external surfaces of the mould are systematically machined, the internal channels are not accessible for machining. Many parameters such as powder size distribution, parameter set, and surface inclinations have an impact on the surface aspect [21]. Even if some technical option such as abrasive flow machining [8] can be used to reduce the roughness in the channels, it is quite difficult to have homogeneous results especially if they are long and thin (below 4 mm). Moreover, those treatments increase the price and the delay to produce a mould insert. Another issue is the difficulty to estimate this roughness and control the quality of the insert after abrasive flow machining (AFM).

It has been observed, for almost two centuries, that the fatigue phenomenon is the main cause of failures seen in service. Understanding it throughout the design process of a mechanical part or for the qualification of a new manufacturing process is essential to ensure their reliability. Due to the emergence of additive manufacturing for metallic materials, many publications have emerged to evaluate the influence of manufacturing parameters on fatigue life [22, 23]. In addition to the factors influencing the lifetime such as loads and the environment, the microstructure has a major role. Indeed, the presence of defects (pores, lack of fusion, insufficient recovery, etc.) especially in under lay has adverse effects on fatigue performance [24]. A large roughness can also have a significant impact on the crack initiation time. It has been observed on some works [25], and those presented here, that the resumption of the raw surfaces by machining could eliminate the defects present in the underlay, improve the surface condition and therefore generate a gain on the

![Fig. 1](image1.png) (left) Hybrid tooling part made by LPBF: the bottom of the part is machined, while the top is 3d printed. (right) Conformal cooling channels in blue mapping the moulding surface of the tool. Photo courtesy of IPC and CONTITECH [18]

![Fig. 2](image2.png) Cooling channel (8 mm diameter) of an injection mould insert after use: (left) traditional drilling; (right) AM cooling channels in maraging steel

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fatigue performance. However, this option is not possible for complex internal channels.

The random nature of this phenomenon makes it difficult to predict, so several tests should be carried out to assess its variability. The most common representation that can be found in the literature is the Wöhler curve also called the SN curve. It relates the cyclic stress imposed on the material to the number of cycles at failure. This curve is obtained by carrying out normative tests [26] on calibrated test specimens for a constant load ratio at different stress levels. The aim of the fatigue tests presented in this study being to make a quick comparison on the fatigue performance of the different manufacturing methodologies, the choice to test all test specimens on a single level of stress, was preferred [27].

In this study, to assess the effect of internal cooling channels on fatigue properties, fatigue tests were carried out in samples with inner channels which were used to reproduce what happens in an injection moulding tool with conformal cooling. The external surfaces of the sample were machined to replicate the configuration of a mould. This ensures crack initiation in the internal channel and not in the outer surface. Two different laser strategies were used aiming to reduce the porosity near the channel.

2 Material and printing process

2.1 Powder material

The material used in this study is maraging MS1 steel from EOS (also called maraging 300 or X2NiCoMo18-9-5); the data sheet is available at [28]. The nominal composition of this steel is provided in Table 1.

| C (wt%) | Fe | Ni (wt%) | Co (wt%) | Mo (wt%) | Ti (wt%) | Al (wt%) | Cu, Cr (wt%) | Mn, Si (wt%) | P, S (wt%) |
|---------|----|----------|----------|----------|----------|----------|-------------|-------------|-----------|
| ≤ 0.03  | Balance | 17–19    | 8.5–9.5  | 4.5–5.2  | 0.6–0.8  | 0.05–0.15 | Each ≤ 0.5 | 0.1 | Each ≤ 0.01 |

2.2 Samples, printing parameters, and laser strategies

To obtain specific samples that reproduce what happens in an injection moulding tool with an internal conformal cooling channel, a 3-mm hole was placed within the specimen. Cooling channels in mould insert have various diameters, but 3 mm is a commonly use section as it allows an efficient cooling in small sections without compromising powder evacuation during depowdering. The samples were printed on an EOS M270 LPBF machine. Nitrogen gas was used as a protective atmosphere. The gas pressure was set to 0.58 mbar. No pre-heating was used as it is not a requirement to print maraging steel 300. The hatching strategy was set to stripes 20 mm, which is the standard parameter in EOS systems to print MS1. The samples were printed in three different orientations: horizontal, vertical, and slanted with a 45° angle (cf. Fig. 3), as cooling channels can be oriented in different directions (cf. Fig. 1). A different set of parameters was used for the infill of the sample and for the contour and downskin on the sample (cf. Table 2). In LPBF, the orientation of the sample is affecting both mechanical performances, magnetic properties, and roughness.

Different contour strategies were used around the hole: the standard contour use by EOS print with a 30 µm offset.

Table 2 Printing parameters used for maraging steel

| Speed (mm/s) | Power (W) | Hatching (µm) | Layer thickness (µm) |
|-------------|-----------|---------------|----------------------|
| Infill      | 750       | 195           | 100                  | 40                    |
| Contour     | 400       | 120           | N/A                  | 40                    |
to the original surface (cf. Fig. 4a) and a new strategy with an additional contour with a 60 µm offset (cf. Fig. 4b). These parameters are available in EOS print and labelled “Contour” and “Postcontour.” The contour and postcontour parameters were used all along the internal channels. These parameters are particularly important for internal channels, which are not machined and which generate high concentration stresses during the tool lifespan.

2.3 Heat treatments

Two different heat treatments are possible for maraging MS1. The usual treatment is a solution annealing (900 °C — 3 h) followed by an aging (490–500 °C — 3 h). Due to the very fast cooling during the manufacturing process, this family of alloys can be directly aged without solution annealing. This second option increases distortion and residual stresses, especially for big parts. Unless otherwise stated, the usual treatment has been performed. In both cases, hardness measurements according to ISO 6508–1 gave similar values of 53 ± 1 HRC.

2.4 Machining

For the fatigue tests, specific specimens with an internal channel were used to reproduce what happens in an injection moulding tool with conformal cooling. Only the inner channel was not machined (except for one condition) as it is usually done industrially. Channels are in a raw condition without any other finishing, so the roughness of the inner surface is important and highly depends on the orientation in the bulk. The other surfaces were machined with a $R_a$ close to the one use in injection moulding in order to have the same aspect as a mould surface: after turning, the samples have been manually polished longitudinally. The dimensions are provided in the drawing Fig. 5.

3 Material characterization

3.1 Residual stress measurement

To estimate residual stresses, specimens as described in Fig. 6 were printed. The samples used in this study had an 8-mm hole located at a distance of 2 mm from the surface in order to replicate the behaviour of a conformal cooling channel. All of them were measured without any finishing and without separation from the plate to avoid residual stress release. The samples have not been removed from the substrate for residual stress analyses. An evaluation of residual stresses was performed using two different methods: X-ray diffraction (XRD) for the surface and hole drilling for the depth.

By using atomic planes as strain gauges, X-ray diffractionometry allows the non-destructive measurement of surface residual stress in materials. The residual stress analyses are carried out with “X-Raybot” goniometer by X-Ray diffraction using Cr-Kα radiation diffracted at $2\theta = 156^\circ$ in the atomic plan (211) of steel. These conditions give the strain following the EN 15,305 standard on test methods for residual stress analysis by X-ray diffraction. For one direction $\phi$, 13 angles of incidence $\psi$ ($\psi = 0$ and 6 positive values and 6 negative values) are considered to obtain equivalent interval in the $\sin^2 \psi$ axe and to have $0 \leq \sin^2 \psi \leq 0.5$. The X-ray spot size is adapted to the measurement zone (2 mm of diameter).

The diffraction pattern position is determined by the centred barycentre method developed by CETIM and recognized in the standard. The radiochromatographic constants used for the reflexion plan (211) in the residual stress calculation are $S_2 = 5.83 \times 10^{-6}$ MPa$^{-1}$ and $S_1 = -1.28 \times 10^{-6}$ MPa$^{-1}$.

The hole drilling method is a destructive technique to analyse residual stress based on the equilibrium principle which means that the residual stresses are in equilibrium without any external forces. Therefore, removing a part of stressed material, the stresses state changes and the material
is going to deform to reach a new equilibrium. If we measure the strains, we can calculate the corresponding stresses.

In the hole drilling method, the strain measurement is performed by means of a 3 strain gauges rosette. The hole is drilled at the centre of this rosette, and to obtain the distribution of the residual stresses throughout the thickness, the hole is drilled step by step. For each step, the strains on the three gauges are measured. With special finite element calculation, the residual stress is determined. Residual stress measurements have been performed by the hole-drilling strain-gage method following ASTM E837-20. The ASTM E837 standard is used to obtain a profile up to 1 mm thickness for a diameter of 2 mm (see Fig. 7b).

### 3.2 Tensile and fatigue testing

Prior to the fatigue tests, tensile tests on two specimens for each condition were performed according to ISO 6892–1—method B—to determine the performance of AM maraging steel at room temperature and at 160 °C, a typical temperature encountered in injection moulds when injecting commodity polymers (PP, PET, PE, ABS). Machined test specimens of round cross-section were used with a nominal diameter of 6 mm.

The high cycles axial fatigue tests were carried out on a 100-kN hydraulic machine (MTS) at room temperature. 27 tests were performed using the geometry presented in Fig. 5. The stress ratio was equal to −1, and the test frequency was set to 10–25 Hz. The lifetime target for a mould insert is usually set from 1 to 10 million parts. For this reason, a censorship criterion for the fatigue testing was set to $10^7$ cycles.

### 3.3 Microstructural analysis

Microscopic examination of samples was performed after several polishing using a series of fine sandpapers and crystal solution with a size of 1 µm for the last step. Observations were firstly done on unetched specimens on an optical microscope (LEICA CTR6000) in order to observe porosity, inclusions. No quantitative analysis was performed as it is hard to distinguish some inclusions from porosities. For etching, a small quantity (2–4 ml) of nital solution (96% ethanol, 4% nitric acid) is deposited on the surface of the sample for about 10 s. Then, the samples were observed using a scanning electron microscope (SEM Zeiss 1455 LEO VP). Using SEM images and backscattered electrons, it was possible to segment porosities from inclusions.
4 Results and discussions

4.1 Roughness measurement

AM process is known to create a roughness, which depends on the inclination of the surface in relation with the building orientation [5] along with mechanical and magnetic properties [29]. The roughness of an upskin surface with already molten material underneath is smaller than that of a downskin surface that has an unfused powder bed underneath. Therefore, it was expected that vertical specimens have a uniform roughness in the channel. The roughness measurement performed in the channel (Fig. 8) clearly showed that on vertical configuration, roughness is homogeneous, whereas for horizontal and 45° configurations, roughness is higher in downskin. Due to this observation, the drop of mechanical performances due to the presence of the internal channel is expected to be more critical for the horizontal and slanted samples than for the vertical ones.

4.2 Residual stresses

The evaluation of residual stresses was carried out in the as-built condition and in the aged condition. The results show that aging significantly reduces them: the residual stresses were divided by three (Fig. 9) compared to the as built condition. Residual stresses were expected to be strongly reduced after a heat treatment including an annealing step at 900 °C due to the temperature reached.

The initial value depends on the shape and massiveness of the parts produced, but also on the process parameters used: indeed, the three last layers of the top surface were produced...
using a specific set of parameters (Table 2) with remelting to ensure a low roughness. It is the main hypothesis to explain why residual stresses are negative at the surface before becoming positive in the depth. While compressive stresses can have a positive influence on fatigue performances, they are also responsible for macroscopic deformation in large tools and thus should be reduced as much as possible in order to limit the risk of high distortion of the part.

Even if residual stresses are lower after aging, small distortions are still expected in the part. It is possible to cut the part in the as-built state, but in this case, shape distortion will be important. Due to the absence of baseplate, the weight in the furnace is reduced during heat treatment which is a solution for small parts with large geometric tolerances. Another option is to perform the aging first and then separate the part from the manufacturing tray aiming to limit shape distortion. The last option is to perform a solution heat treatment at a higher temperature which virtually eliminates residual stresses. The deformations are thus reduced to a minimum. This option is considered the most appropriate for large part, such as mould insert and thus was selected in this study in order to reduce the impact of the residual stresses on the fatigue measurement.

4.3 Tensile and fatigue testing

The values obtained (Table 3) are typical for this alloy. No anisotropy due to the process can be identified. At 160 °C, an expected decrease in mechanical properties (Rm and Rp0.2) is observed.

Fatigue tests were carried out at a unique stress level for all test specimens at room temperature and 160 °C. Figures 10 and 11 present the results on stress versus the number of cycle graphs in semi-log scale for ambient temperature and 160 °C, respectively. Log-normal distribution laws are also plotted on these graphs to illustrate the median life and the deviation of all specimen conditions. Because of 3 no failures on the “vertical and machined channel” specimens, the log-normal distribution curve was not plotted. Table 4 resumes the main value for each orientation and temperature. Several statistical tests on median and standard deviation (cf. [30]) were realized to demonstrate the equivalence (or not) between each kind of sample. The distribution law of lifetime is assumed to be log-normal, so all statistical analyses were done in the log base.

As the inner channels were not machined, roughness and defects generate high stress concentration and the failure

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![Residual stresses measurements](imageurl)

Fig. 9 Residual stresses measurements made by XRD and hole drilling in two directions

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Table 3 Results of tensile test performed at 20 °C and 160 °C in both horizontal and vertical direction of production

| Direction   | Temperature | Ultimate tensile strength, Rm (MPa) | Yield strength, Rp 0.2 (MPa) | Elongation, A (%) | Reduction of Area, Z (%) |
|-------------|-------------|------------------------------------|------------------------------|-------------------|--------------------------|
| Horizontal  | 20 °C       | 1959±2                             | 1859±32                      | 5.7±0.5           | 20±2                     |
| Vertical    | 20 °C       | 1960±9                             | 1874±13                      | 4.8±0.4           | 21±1                     |
| Horizontal  | 160 °C      | 1766±5                             | 1695±25                      | 7.0±1.2           | 17±1                     |
| Vertical    | 160 °C      | 1779±8                             | 1697±33                      | 4.5±1.3           | 20±1                     |
always initiated from the internal channel in all the tested samples. The external surfaces were fully machined, polished, and have a low roughness (Ra < 0.2 µm).

It is observed that a temperature of 160 °C slightly decreases the fatigue lifetime for 45° and vertical orientation, which can be linked to the fact that the strength of maraging steel is slightly reduced at 160 °C [31]. For the horizontal orientation, fatigue life is higher at room temperature compared to 160 °C, which is not explained at the moment but is under investigations. However, fracture surface observations do not show any difference. Crack initiation sites are all observed on the roughest surface in the downskin area. Moreover, as expected samples with machined channel give the best results with no broken samples before the censorship. Vertical samples break first, whereas the roughness is higher for inclined and horizontal samples. As you can see in Fig. 12a, several radial lines are present on the fatigue fracture surface. Therefore, several crack initiation sites are
present at the internal surface. Fracture analysis showed many defects measuring greater than 100 μm on the vertical specimens between the core and the contour of the part (Fig. 12b, c). Those defects are also visible on horizontal and 45° samples but are fewer in number. The same defects are also visible on micrographs (Fig. 12d). Thus, the root cause of the initiation site is the presence of defects even if roughness and inclusions also contribute but with a less impact on crack initiation.

It was then chosen to optimize the printing parameter in order to reduce as much as possible the contour defects. As presented previously (Sect. 2.2), a second inner contour has been added with an offset of 60 μm (towards the interior of the sample), aiming to reduce interfacial porosity between infill and contour as illustrated in Fig. 4b. A second vertical batch obtained by these new machining parameters was tested in the same conditions (room temperature and 160 °C). Micrograph (Fig. 13) shows that porosity between contour and core was strongly reduced. Only a few porosities are observed in the core.

Because of the 3 no failure tests, the normal distribution curve for the second vertical batch at 160 °C cannot be plotted. As can be seen in Fig. 14, the fatigue performance with a second contour is enhanced very significantly for both configurations: room temperature and 160 °C. Table 5 resumes the main value for each vertical batch and temperature. The new laser strategy strongly increases the lifetime by more than a decade. This point demonstrates that defects previously observed are very harmful for the fatigue behaviour.

**Table 4 Results of fatigue test performed at RT and 160 °C**

| Temperature | Orientation            | Median lifetime, N | log(N) | Standard deviation, \(\sqrt{\log(N)}\) | Equivalence with |
|-------------|------------------------|--------------------|--------|----------------------------------------|-----------------|
| RT          | 45°                    | 430,930            | 5.63   | 0.05                                   | Vertical        |
|             | Horizontal             | 1,202,788          | 6.08   | 0.16                                   | None            |
|             | Vertical               | 398,054            | 5.60   | 0.07                                   | 45°             |
|             | Vertical+machined channel | -                 | -      | -                                      | -               |
| 160 °C      | 45°                    | 208,143            | 5.32   | 0.07                                   | Vertical, horizontal |
|             | Horizontal             | 229,216            | 5.36   | 0.09                                   | 45°, vertical   |
|             | Vertical               | 170,717            | 5.23   | 0.08                                   | 45°, horizontal |
|             | Vertical+machined channel | -                 | -      | -                                      | -               |

![Fig. 12](image) **Fig. 12** a Global view of the broken sample in cross section. b and c SEM observation of a fractured surface after fatigue test on a vertical sample with many defects between core and contour. d Similar defects seen on an optical micrograph with etching on a vertical sample (as-built condition)
Whereas it is expected a better behaviour at room temperature, no relevant difference can be made between room temperature and 160 °C for this new and better strategy. Indeed, at 160 °C, two samples broke before the median lifetime at room temperature but 3 did not break. To highlight a difference, a larger number of samples or higher stress level could be considered in the future.

A significant difference between the standard deviations of both laser strategies is observed for the tests realized at room temperature, and it could be assumed the same observation for 160 °C tests. This could be explained by the position of these points on their respective SN curve. Indeed, for the additional contour laser strategy, the lifetimes tend toward the fatigue limit (very high cycle fatigue

| Temperature | Laser strategy          | Median lifetime, $N$ | Median lifetime, $\log(N)$ | Standard deviation, $s_{\log(N)}$ |
|-------------|-------------------------|----------------------|-----------------------------|----------------------------------|
| Room temperature | Standard (1 contour) | 398,054 | 5.60 | 0.07 |
|   | Additional contour | 6,307,528 | 6.80 | 0.12 |
| 160 °C | Standard (1 contour) | 170,717 | 5.23 | 0.08 |
|   | Additional contour | - | - | - |
domain) where the fatigue results do not follow a lognormal distribution.

5 Conclusion
A double concentric contour will drastically improve the fatigue life of moulds made of maraging 300 steel by laser melting on powder bed. The channels positioned near the surface to ensure optimal cooling are usually left unfinished and present a significant amount of small pores that can promote the initiation of fatigue cracks. Contour parameters are generally optimized to improve the surface aspect but not the mechanical performance. In this case, this roughness proved to be less important than the defects — lack of fusion — resulting from the parameters used between the core and the contour. The defect could be resolved by modifying the parameters and adding a second contour line. The positive impact on fatigue life of the components was proven both at room temperature and at 160 °C. While a lot of studies focus on finishing strategies to reduce the roughness using for instance abrasive flow machining, it is key to combine this work with laser strategies optimization as porosity close to the surface are also likely to affect the fatigue lifespan of a manufactured part. The analysis should also be performed on other materials, such as stainless steel and the impact of a higher temperature are between 300 and 550 °C.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Code availability N/A; no codes have been written for this study.

Declarations

Ethics approval N/A; the experiments did not involve any human participants.

Conflict of interest The authors declare no competing interests.

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