

Optimizing the connection mode between two diameter-varied conformal cooling channels in a selective laser melting-fabricated mold

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Abstract: The conformal cooling channels (CCCs) can improve the cooling efficiency of die casting molds, but improper designing might induce larger residual stress, especially for molds with diameter-varied CCCs. The effect of connection mode on the stress between two diameter-varied CCCs was studied by finite element analysis. The value and position of the maximum stress differ between the surface and the internal CCCs. For a fixed radius difference (a) of two diameter-varied CCCs, the increase of the length (b) of the transition region not only leads to the gradual decrease of the maximum stress, but also shifts the stress concentration position from the transition region between two diameter-varied CCCs to the parallel region with a smaller CCC diameter. Under the condition of a permanent wall thickness, the value of b should be at least twice of a value so as to avoid serious structural stress. The results of mechanical performance test for the 18Ni300 maraging steel, fabricated using selective laser melting method, verified the validity of simulation. Samples with the absolute value of a/b above 1/2 present brittle fracture behavior, otherwise possessing good tensile ductility.

Keywords: stress; conformal cooling channels; finite element analysis; selective laser melting; 18Ni300

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1 Introduction

Die casting mold has been widely used in hot metal forming industry. However, the extreme working conditions involving thermal and mechanical (thermo-mechanical) loadings, which result from the direct contact between the tools and the hot workpiece, lead to the damage of molds^[1].

Particularly, the sudden and sharp temperature changes of mold result in alternative compressive and tensile stresses during hot forming operations, which is known as thermal fatigue damage^[2, 3]. Therefore, a straight-in and straight-out cooling channels are incorporated to accelerate cooling, thus reducing thermal stress caused by large thermal gradients^[4]. However, the cooling efficiency of this straight-in and straight-out cooling structure is limited, and heterogeneous temperature distribution induced thermal stress still has great impact on the mold life.

Recently, conformal cooling channels (CCCs) with complex internal shape can be realized through additive manufacturing (AM) methods such as selective laser melting (SLM)^[5-8]. Actually, AM methods have great advantages in freedom manufacturing capability,

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which are especially suitable for fabricating die casting molds with complex external topology as well as intricate internal structure^[9-11]. CCCs can improve the production efficiency and reduce product deformation because of its high cooling rate and homogenous temperature distribution^[12-15]. Therefore, extensive studies have been performed to optimize the CCCs design for die casting and injection molds. Previous studies have suggested that the use of CCCs in molds can improve the precision of mold temperature control and enhance part dimensional accuracy. For example, Jahan et al.^[16] investigated the heat distribution of different shaped CCCs and revealed that rectangular cooling channels exhibited the best cooling efficiency without causing deformation at the cross-sectional area. Li et al.^[17] have designed a series of CCCs with various shapes and suggested that the CCCs featuring a flat-head layout offered the shortest cooling time and the fastest cooling rate. The aforementioned results indicate that internal CCCs of 3D-printed molds can significantly shorten single cycle time and improve production efficiency.

However, for complex mold geometries, it becomes necessary to vary the diameter of internal CCCs to enhance cooling efficiency while ensuring adequate structural strength. An improper connection between two CCCs with different diameters can lead to significant structural stress. Most studies have focused on the stress caused by factors such as channel shape, size, and distribution. Mazur et al.^[18] conducted a numerical analysis to access the stress concentration in circular CCCs and demonstrated that the stress increased with larger channel diameters and shorter channel depths and distances. A novel scaffolding architecture of CCCs can ensure more uniform thermal distribution while simultaneously mitigating large residual stresses within the plastic injection mold^[19]. A self-supported structure was designed inside the large CCCs by Tan et al.^[20] to suppress the collapse and warpage caused by the stress from solidification shrinkage while retaining a higher cooling rate. Generally, the structure of incorporated CCCs should be designed to minimize structural stress and deflection of the mold, while maintaining excellent cooling efficiency. Numerical simulations have indicated a reduction in stress concentration by over 50% when using round-shaped CCCs^[21]. While, the influence of connection mode on the stress between two CCCs with varying diameters has been rarely reported in literature.

Finite element analysis (FEA) has been confirmed a reasonable method for stimulating the stress in molds containing internal CCCs^[22, 23]. In this study, a model containing CCCs with varying diameters was designed using UG NX software, and subsequently imported into ANSYS Workbench for the stimulation of stress distribution. The reliability of simulation results was further examined by SLM-fabricated 18Ni300 maraging steel (MS). The 18Ni300 MS, as a typical age-hardenable martensite steel^[24, 25], has been widely used in welding and mold industries^[25-27] due to its excellent mechanical properties including high strength, high toughness, and good weldability. SLM-fabricated 18Ni300 MS exhibits better mechanical properties than the counterpart prepared by conventional methods such as forged and aged^[28, 29]. This study will shed a light on the designing of SLM-fabricated die-casting molds incorporating CCCs with various diameters.

2 Experimental

A cylindrical tensile-shaped model with an internal hollow conformal cooling channel was built using UG NX 10.0, as shown in Fig. 1. The wall thickness of the hollow CCCs was fixed to be 2 mm. The radius of hollow CCC in Region C was fixed to be 1 mm, which increased to be $(a+1)$ mm in Region A. The transition Region B located between Region A and Region C has a length of b (in mm). In this study, a set of a/b ratios (Table 1) was applied to investigate the influence of a/b ratio on the value and distribution of stress.

The designed model was imported into ANSYS Workbench 2020 to simulate the static stress distribution. The mean size of the tetrahedral-type mesh was 2.25 mm, as shown in Fig. 2(a). The left side of the model was fixed, while a tension load of 8,000 N was applied in the right side [Fig. 2(b)]. The material parameters used in FEA, as listed in Table 2, were obtained from related literature^[30-34].

The accuracy of the simulation was further verified through SLM-fabricated 18Ni300 MS. The morphology of the gas-atomized pre-alloyed 18Ni300 MS powder was observed using a Zeiss/Gemini scanning electron microscope (SEM 360), as shown in Fig. 3(a). The powder consists of spherical-shaped particles, with some satellite powders adhered to the main particles. Figure 3(b) reveals that the average particle size (D_{50}) is approximately 31.0 μm , with the particle size distribution

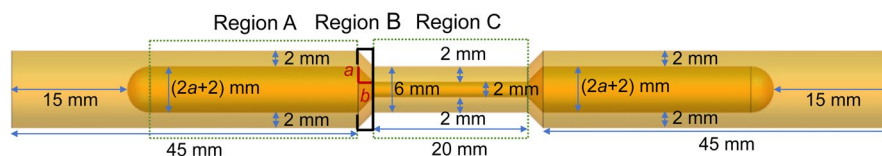


Fig. 1: Schematic diagram of model geometry

Table 1: Values of a and b for different cases (mm)

Cases	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	B7	B8
a	2	2	2	2	2	2	3	3	3	3	3	3	3	3
b	2	3	4	6	8	10	2	3	4	5	6	9	12	15

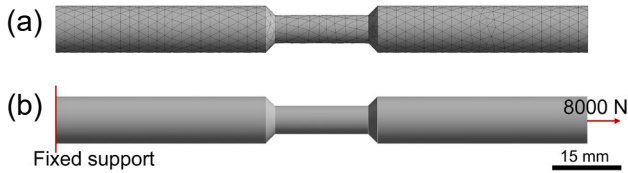


Fig. 2: Model for stress simulation: (a) tetrahedral-type mesh; (b) boundary conditions

Table 2: Material parameters used in FEA

Density	Young's modulus	Poisson's ratio	Tensile yield strength
8 g·cm ⁻³ [30]	153 GPa ^[30]	0.28 ^[31]	1,100 MPa ^[30, 32-34]

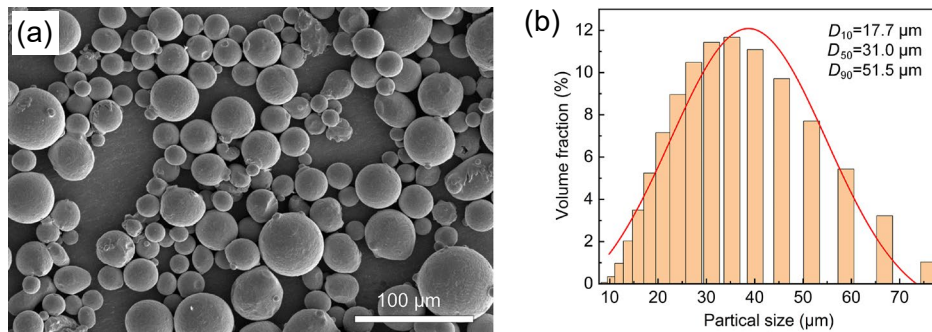


Fig. 3: 18Ni300 MS powders used in the experiment: (a) SEM particle morphology; (b) particle size distribution

Table 3: Chemical compositions of 18Ni300 MS powder (wt.%)

C	Co	Ni	Ti	Mo	Fe
0.026	8.8	18.64	0.65	4.8	Bal.

The samples for microstructural investigation underwent etching in an etchant of 4% nital for 20 s before observing using a Leica DMIRM optical microscope (OM) and a Zeiss/Gemini scanning electron microscope (SEM 360). Room temperature tensile experiments were conducted on a Zwick/Roell Z100 universal testing machine at a rate of 0.15 mm·min⁻¹. The tensile direction was oriented along the *X*-axis for these samples. For each condition, at least three samples were tested to ensure reproducibility.

3 Results and discussion

Figure 4 shows the equivalent stress distribution of the samples when *a* is fixed to be 2 mm with *b* ranging from 2 to 10 mm. The dividing line of different stress regions on the surface is smooth, and no stress mutation is observed, indicating the reliability of the model used in the current work. It can be observed that the maximum stress of the model surface is always larger than that of the internal CCCs. For example, the maximum stress on the model surface of Case A1 (*a*=*b*=2 mm) is 578.34 MPa, but that of the internal CCC is 467.22 MPa [Fig. 4(a)]. The increase of *b* value leads to the gradual decrease of maximum stress both on the model surface and in the internal CCCs. When *b* reaches

ranging from 17.7 μm (*D*₁₀) to 51.5 μm (*D*₉₀). The chemical compositions of the 18Ni300 MS powder are listed in Table 3.

The tensile samples of 18Ni300 MS were manufactured using a commercial HT 250 series machine (Ningbo Haitian Additive Technology Co., Ltd., China), which was equipped with a 500 W Yb-Fiber laser operating at a wavelength of 1,064 nm and boasting a maximum speed of 8,000 mm·s⁻¹. The optimal laser parameters were as follows: laser power (*P*) was adjusted to 300 W, scanning speed (*v*) was set at 1,100 mm·s⁻¹, layer thickness (*t*) was 50 μm, and the hatching distance (*h*) was 80 μm. The volume energy density was evaluated to be 68.18 J·mm⁻³. After the completion of each layer, the scan direction was rotated by 67°. The detailed information about SLM process can be found in Ref. [25].

10 mm (Case A6), the maximum stress on the surface is 342.32 MPa, which is very close to that of the internal CCC, 337.08 MPa [Fig. 4(f)]. The position of the maximum stress changes between the surface and the internal CCCs, indicating a dependence on *a/b* ratios. When *b* reaches 8 mm and above, the position of maximum stress on the surface shifts from the adjacent area between Region B and Region C [Figs. 4(a-d)] to the parallel area of Region C [Figs. 4(e-f)]. With respect to the internal CCCs, the initial position of the maximum stress locates in the adjacent area between Region A and Region B, which changes to the parallel area of Region C when *b* is 4 mm and above.

Similar phenomenon is observed in those models when *a* is set to be 3 mm, as shown in Fig. 5. The maximum stress on the surface and internal CCC of Case B2 (*a*=*b*=3 mm) is 558.74 MPa and 466.04 MPa, respectively. Both are smaller than those of Case A1 (*a*=*b*=2 mm). When the applied force is fixed, the normal stress along the tensile direction is inversely proportional to the cross-sectional area. The increase of *a* value leads to a larger cross-sectional area, thus reducing the maximum stress^[35]. However, the overall trend keeps unchanged. The maximum stress again decreases with increasing *b* value, and its position progressively changes to the parallel area of Region C (Fig. 5).

The maximum stress of the samples with different *a/b* ratios is summarized in Fig. 6. The model without internal CCCs was also simulated for comparison. It can be distinctly observed that samples with CCCs possess a greater structural stress on the surface than those without CCCs under the same applied

load, although the value of the maximum stress decreases with the increase of b value at a fixed a value. Simultaneously, the difference of the maximum stress between the surface and the internal CCCs becomes smaller at a higher b value. When b reaches 4 mm and above, the maximum stress on the surface of the samples without CCCs is close to that of the internal CCCs.

According to the simulation results, it is reasonable to speculated that the length (b) of the transition region should be at least double the value of a . This conclusion arises because, when the absolute ratio of a/b falls to 1/2 or below, the position of the maximum stress of internal CCCs shifts from the adjacent area between Region A and Region B to

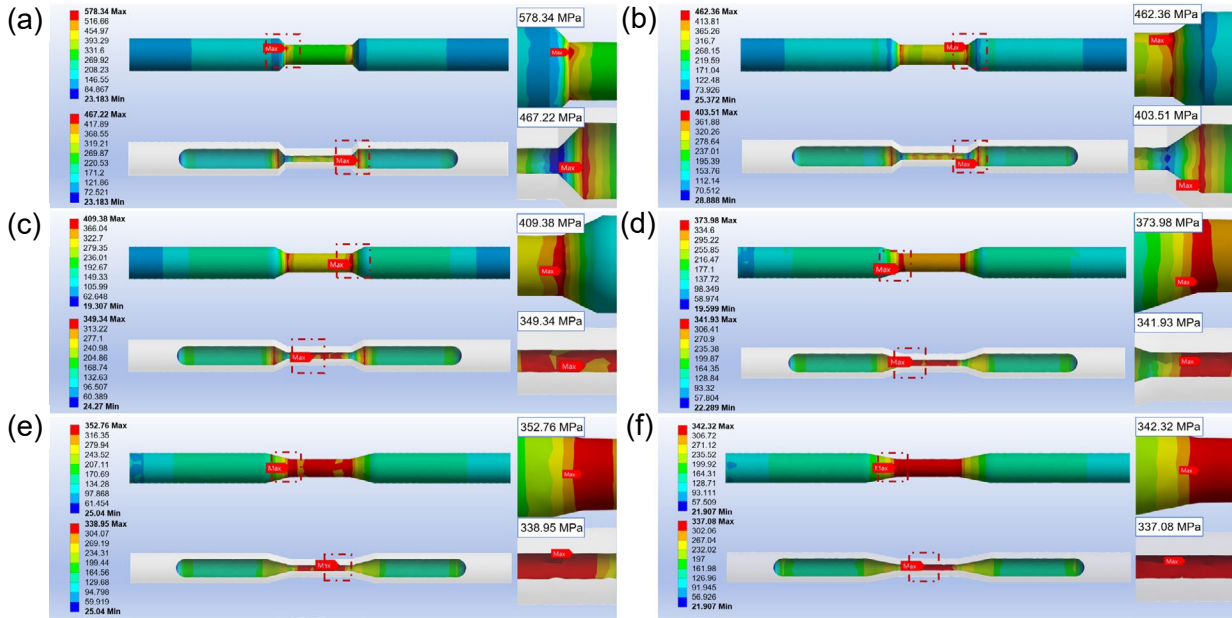


Fig. 4: Equivalent stress and its distribution of the samples when a is 2 mm while b ranging from 2 to 10 mm: (a) Case A1: 2/2; (b) Case A2: 2/3; (c) Case A3: 2/4; (d) Case A4: 2/6; (e) Case A5: 2/8; (f) Case A6: 2/10

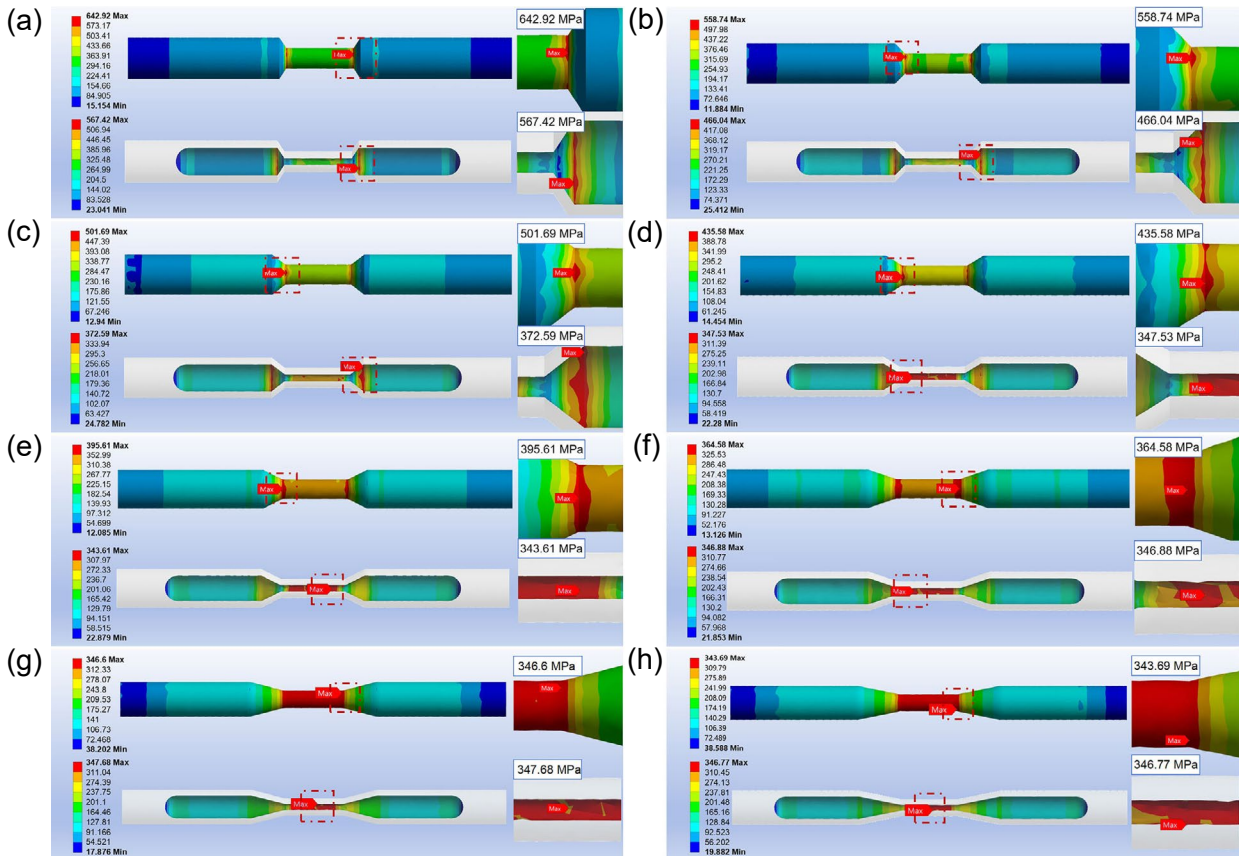


Fig. 5: Equivalent stress and its distribution of the samples when a is 3 mm while b ranging from 2 to 15 mm: (a) Case B1: 3/2; (b) Case B2: 3/3; (c) Case B3: 3/4; (d) Case B4: 3/5; (e) Case B5: 3/6; (f) Case B6: 3/9; (g) Case B7: 3/12; (h) Case B8: 3/15

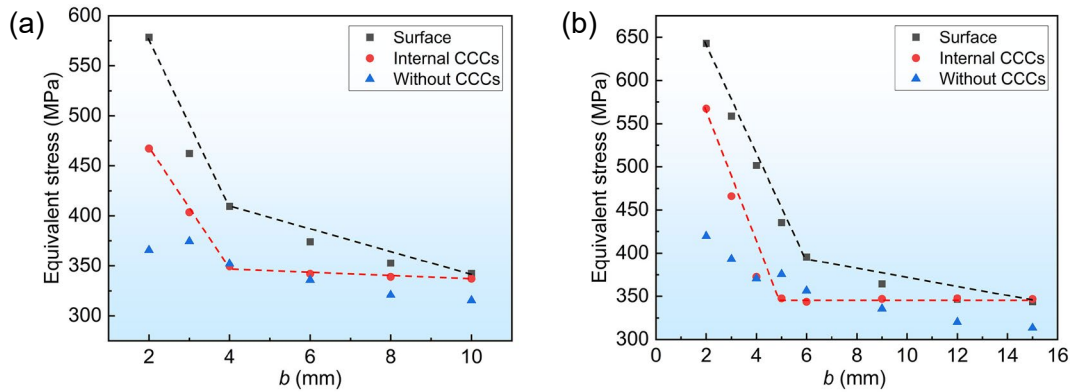


Fig. 6: Maximum equivalent stress of all cases: (a) $a=2$ mm; (b) $a=3$ mm

the area of Region C. In order to validate the aforementioned simulation results, several representative cases were selected for experimental testing.

SLM-fabricated 18Ni300 MS cylindrical tensile samples are shown in Fig. 7(a). Figure 8 illustrates the room temperature tensile curves of samples with different a/b ratios. It can be observed that the samples exhibit better mechanical properties when the a/b ratio no more than 1/2. The ultimate tensile strength (UTS) for the specimens with a/b ratios of 2/4, 2/6, and 3/6 is measured as $1,114 \pm 5$ MPa, $1,106 \pm 7$ MPa, and $1,112 \pm 7$ MPa, respectively. The corresponding elongation (EL) values for these three specimens are $(7.61 \pm 0.1)\%$, $(8.83 \pm 0.14)\%$, and $(9.08 \pm 0.12)\%$. Particularly, the sample with a/b ratio of 3/2 exhibits the highest stress [Fig. 6(b)], and simultaneously the smallest UTS and EL, as shown in Fig. 8. The overall morphology of samples after tensile tests is shown in Fig. 7(b). This observation is consistent well with simulation results in Figs. 4 and 5. When the maximum stress of internal CCCs concentrates on the adjacent area between Region B and Region C, the samples show the feature of brittle fracture. Obtained experimental results confirm the reliability of simulation.

Mechanical properties can be significantly affected by microstructures. Therefore, both brittle A1 and ductile A4 samples were chosen to investigate the microstructure. The cylindrical tensile samples were cut off from the adjacent position between Region B and Region C. There are no obvious defects such as micropores on the surface, as shown in Figs. 9(a) and (d), indicating higher quality of SLM-fabricated samples. Figures 9(b) and (e) display the motion tracks of

laser radiation across the horizontal cross-section. The size of the ellipsoid braided structure in the horizontal cross-section measures approximately 90–110 μm in width, which is comparable to the laser spot diameter of around 100 μm . SEM images in Figs. 9(c) and (f) still reveal analogous cellular structure and equiaxial grains. Therefore, the difference in mechanical performance can be attributed to structural discrepancy rather than microstructure.

Both the simulation observations and tensile tests indicate that different a/b ratios have significant impact on the equivalent stress and its distribution. When the absolute value of a/b reaches 1/2 and below, the position of the maximum stress tends to locate in the parallel area rather than the transition area (Figs. 4 and 5). This observation is in accordance with the tensile properties at room temperature, as shown in Figs. 7 and 8. Samples with an absolute value of a/b greater than 1/2 exhibit brittle fracture behavior, while those with an absolute value of a/b less than or equal to 1/2 possess good tensile ductility. It should be noted that the UTS of these samples with internal CCCs is slightly lower than that of the samples without CCCs (as shown by the blue triangle in Fig. 6), when fabricated under the same SLM parameters. Additionally, there is a noticeable decrease in EL in comparison to samples without CCCs^[25]. The UTS and EL of SLM-fabricated 18Ni300 MS are 1,141 MPa and 11.73%, respectively^[25]. The decrease of both UTS and EL induced by internal CCCs must be taken into consideration for mold structure design.

Meanwhile, the difference in the maximum stress between the surface and the internal CCCs gradually decreases with

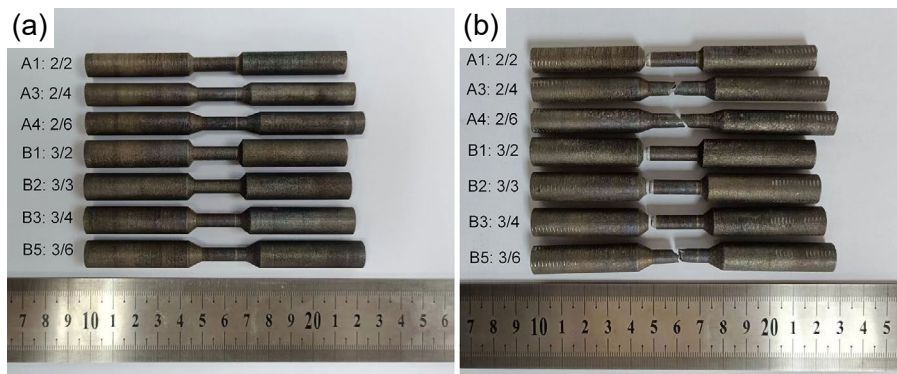


Fig. 7: SLM-fabricated samples: (a) as-printed; (b) after tensile tests

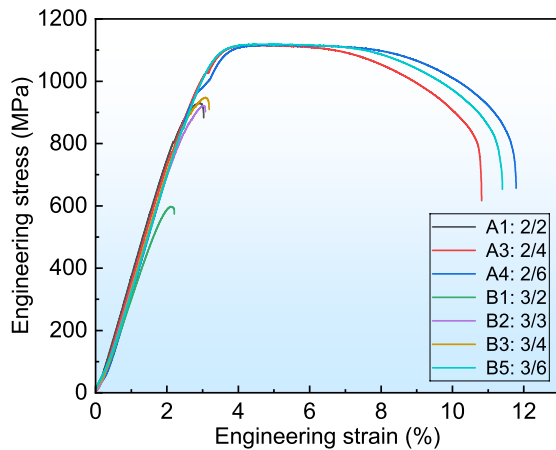


Fig. 8: Room temperature tensile curves of samples with different a/b ratios

the decline of the absolute a/b values, as shown in Fig. 6. Particularly, when the absolute value of a/b reaches $1/5$, the maximum stress of the internal CCCs is almost the same as that of the surface. The results obtained can provide valuable reference for the design of casting mold insert with diameter-varied CCCs. Under the condition of a fixed wall thickness, the length (b) of the transition region should be at least double of the radius difference (a) between two diameter-varied CCCs, so as to avoid serious structural stress. However, a longer transition length can also be avoided, since the maximum stress tends to reach a steady value when the absolute value of a/b is $1/5$. In addition to the findings reported in previous literature regarding the layout, size, and scaffolding architecture of CCCs^[18, 19, 36], the results of this study offer guidelines for designing CCCs with varied diameters.

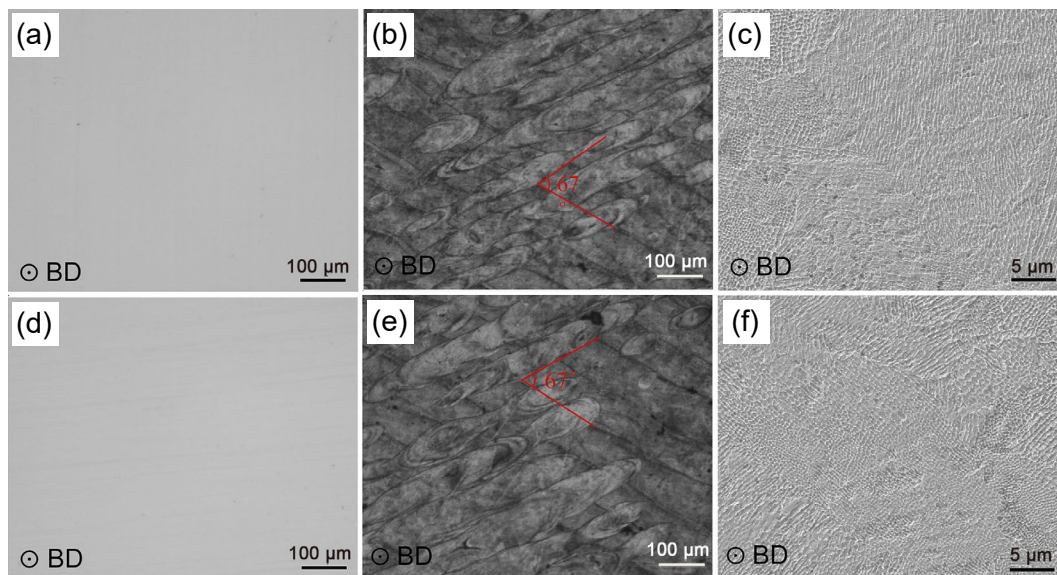


Fig. 9: OM and SEM images of SLM-fabricated specimens: (a–c) Case A1: 2/2; (d–f) Case A4: 2/6

4 Conclusions

In this work, the maximum stress and its distribution of CCCs with varied diameters was studied through FEA. SLM-fabricated 18Ni300 MS was further introduced to verify the validity of simulation results. The following conclusions are obtained:

(1) The value and position of the maximum stress differ between the surface and the internal CCCs. The maximum stress of the surface is always greater than that of the internal CCCs, but the difference becomes smaller at a larger length b value. When the radius difference between two CCCs is fixed to be a , an increases in the length of transition region (b) will lead to a gradual decrease in the maximum stress of both surface and internal CCCs. Furthermore, it shifts the location of stress concentration from the transition region between two CCCs with different diameters to the parallel region with a smaller CCC diameter. To avoid significant structural stress, when the wall thickness is fixed, the length (b) of the transition region between two CCCs with different diameters should be at least twice the radius difference (a) between them.

(2) The results of mechanical performance test on the SLM-fabricated 18Ni300 MS verify the validity of simulation. Samples with an absolute value of a/b greater than $1/2$ present brittle fracture behavior, otherwise exhibit good tensile ductility. Compared to the samples without CCCs, the incorporation of internal CCCs leads to a slight decrease of UTS and an apparent decline of EL.

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Conflict of interest

The authors declare that they have no conflict of interest.

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