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# Study on Composite Design Suitable for High Hardness and Strong Abrasive Formation

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## ABSTRACT

PDC (Polycrystalline Diamond Compact bit) composite is the most important cutting element of petroleum bit, which performance directly affects the service effect and service life of the bit. During the drilling process, the cutter will produce a large amount of friction heat when cutting the rock, resulting in a sharp increase in the internal temperature of the cutter. When the temperature reaches a certain value, thermal wear and tear are very easy to occur, which will not only cause diamond delamination but also reduce the wear resistance of the cutter. Under the action of impact load, impact failure is more likely to occur, which greatly reduces the service life of the cutter and the rock-breaking efficiency of the drill bit. Therefore, this paper studies the composite interface suitable for high-temperature drilling through the changes of cutting tooth temperature field and stress field with different interface shapes, which shows that the non-planar interface is more suitable for improving the cutting tooth life of composite under the action of comprehensive stress field.

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# 1. Introduction

During drilling, the performance of polycrystalline diamond compact has gradually attracted extensive attention with the wide applications of PDC bits (as shown in Fig. **1**) [1, 2]. The polycrystalline diamond composite sheet is sintered by a diamond layer and tungsten carbide matrix under high temperature and high pressure. According to the manufacturing process conditions [3-5], 1000 ℃ is generally taken as the stress relaxation temperature and room temperature is 25 ℃ to analyze the residual stress at different interfaces, so as to observe the performance advantages of the composite sheet. At present, non-planar connection technology and gradient transition technology are mainly used to improve the performance of the cutter [6,7]. In addition, adding a small amount of binder can greatly improve the bonding strength between the diamond layer and matrix in the manufacturing process of PDC teeth. And the formation of higher hardness carbides can be filled between diamond grains, so as to increase the favorable influence of graphite and improve the quality of PDC teeth in the sintering process [8,9]. The expansion coefficient of the matrix can be reduced by the diffusion of diamond particles into cemented carbide, and the residual stress at the edge of the PCD layer can be reduced [10]. The uneven combination design has a great impact on the increase of diamond layer thickness and the reduction of residual stress, and can greatly improve the service life of the cutter [11-13]. At the same time, the design of a stiffener can reduce the performance defects of the composite [14-16]. Due to the difference of physical parameters such as thermal expansion coefficient between the diamond layer of cutter and cemented carbide matrix, the thermal expansion coefficient of the matrix is higher than that of a diamond. When the same temperature change occurs, the expansion or contraction of the matrix will be constrained by the diamond layer due to inconsistent deformation, resulting in residual stress [17]. The abnormal failure of fracture and delamination of composite sheet is mostly caused by the residual stress cracking and interface structure of PDC teeth, and the thermal residual stress is the main cause of abnormal failure of PDC teeth [18].

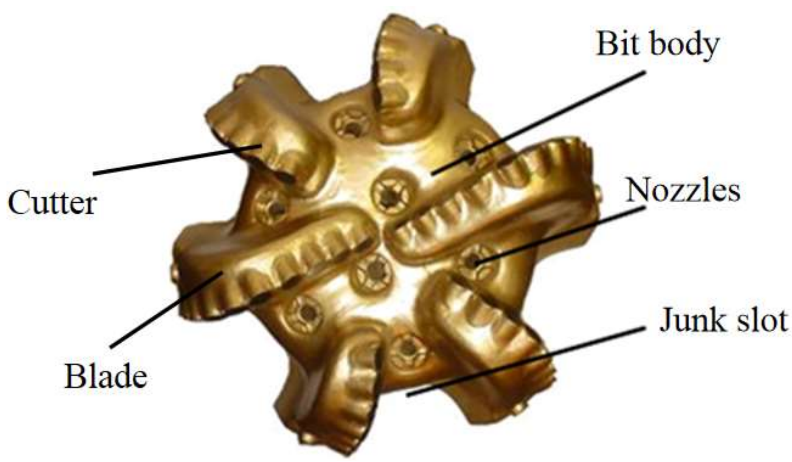


**Figure 1:** PDC bit.

# 2. Failure Analysis

## 2.1. The Collapse Failure

Due to the heterogeneity of the formation, the down-hole formation temperature is high in geothermal drilling, and the influence of various factors during the operation of the bit, such as drill string deformation, formation lithology, bit structure, etc., periodic vibration will inevitably occur, especially when cutting a brittle rock. When the drill bit vibrates, the alternating impact load will continue to act on the PDC teeth, causing the PDC teeth (especially the polycrystalline diamond layer of the teeth) to bear the alternating action of high temperature and cooling, resulting in mechanical fatigue, and tooth collapse under the impact load, as shown in Fig. (**2**). In addition, the high formation temperature is easy to cause the carbide blocks and teeth falling of the upper stabilizer of the bit and the cone bit used in the upper well section. When the PDC tooth drill encounters the falling carbide blocks or teeth, the tooth skipping phenomenon is more serious.

**Figure 2:** The collapse failure.

### 2.2. The Thermal Wear and Delamination Failure

The cutting tooth is the main working element of the PDC bit. The polycrystalline diamond layer is the main part of the cutter, which bears the main working load of the bit. The cutter produces a lot of friction heat in the process of cutting rock. There is a large difference in the thermal expansion coefficient between the polycrystalline diamond layer, hard alloy matrix and bonding phase Co when the temperature reaches a certain degree. When the cooling effect is not enough to reduce the temperature of the teeth to the appropriate range, large internal stress will be generated in the teeth due to the inconsistent thermal expansion of the two materials, and thermal cracks will be formed, resulting in thermal wear of the cutter. As shown in Fig. (**3**), after the cutter is worn out, the friction surface between the teeth and the rock will increase, and more friction heat will be generated during drilling.

**Figure 3:** The thermal wear and delamination failure.

## 3. Study on Interface Stress and Temperature Field of Cutter

In order to study the influence of different bonding interfaces between PDC layer and WC matrix on the performance of cutter, non-plane contact to study the residual stress of cutter and the cutting performance of cutter at high temperature in addition to the conventional plane interface contact. The interface shape used is shown in Fig. (**4**). At the same time, the comprehensive stress of the cutter interface under the joint action of residual stress and cutting process is analyzed. The cutter size is ø 16×10, and the thickest dimension of PCD layer in the model is 2mm and the thinnest dimension is 1mm in the whole model.

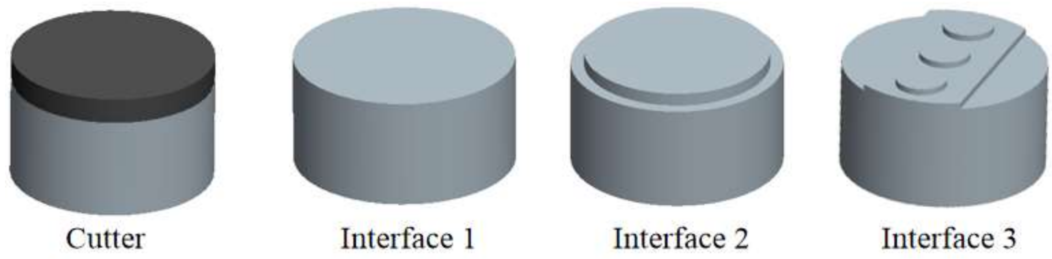


**Figure 4:** The different interface shapes.

### 3.1. Study on Temperature Field of a Cutter Under Different Interfaces

Figure (**5**) is the temperature field change cloud diagram of PDC composite sheet and WC matrix under No. 1 interface when the ambient temperature is 300 ℃, which can be seen that the temperature of PDC composite sheet is higher than that of WC matrix. The temperature gradient change in the temperature field of the PDC composite sheet is small, and the gradient change of WC matrix is large. The main reason is that the temperature of WC matrix mainly comes from the heat conduction effect of PDC composite, and the thermal conductivity of PCD composite is higher than that of WC. From the whole cutter surface temperature, the area with high cutter temperature is still in the interaction area between cutter and rock, which is the concentrated area of plastic deformation between cutter and rock, rock debris and rock. The farther away from the contact area, the lower the tooth surface temperature. On the circumference of the tooth edge, the highest temperature area appears at the lowest part of the tooth edge and then decreases to both sides of the tooth edge.

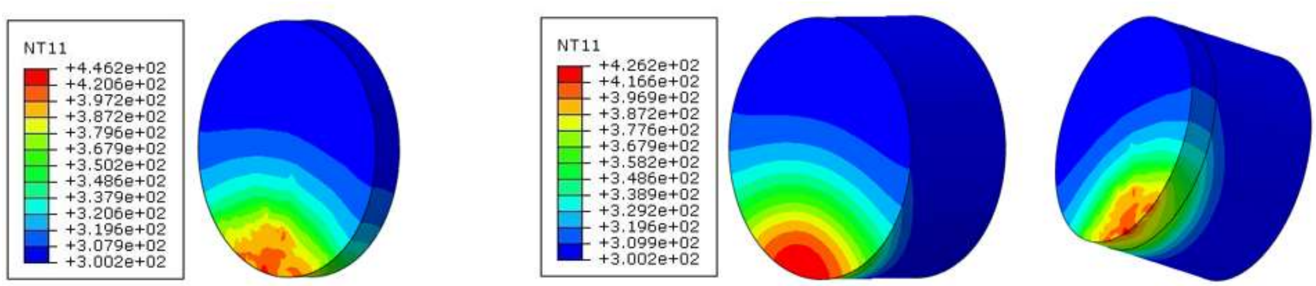


**Figure 5:** The temperature nephogram of PCD composite sheet and WC matrix at interface 1.

The maximum temperature of PCD layer and WC matrix under different bonding interfaces are shown in Fig. (**6**), which can be seen that under different bonding interfaces, the maximum temperature of PCD layer and WC matrix at plane interface 1 is higher than that of a non-plane interface, the main reason is that when the temperature of the non-planar contact PCD layer increases, the contact area of the joint surface expands, so that the cutter disperse rapidly in the heat transfer process, the tooth surface temperature decreases rapidly, and the temperature transmitted to the WC matrix is dissipated, so as to improve the high-temperature resistance, reduce the thermal wear degree of the cutter and improve the service life of the cutter. The non-planar contact, the maximum temperature of PCD layer and WC matrix at No. 2 and No. 3 interface is the lowest, which are 419.4 ℃, 370.7 ℃, 416.3 ℃ and 368.3 ℃ respectively.

### 3.2. Study on Residual Stress Field of a Cutter Under Different Interfaces

The cloud diagram of residual Mises stress of cutter under different interfaces is shown in Fig. (**7**). The maximum residual stress of the cutter under different interfaces mainly acts on the interface between PCD layer

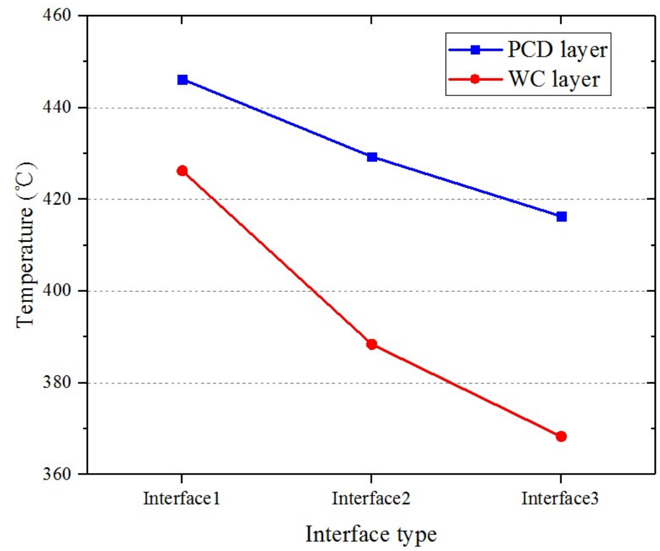


**Figure 6:** The maximum temperature of PCD composite and WC matrix under different interfaces.

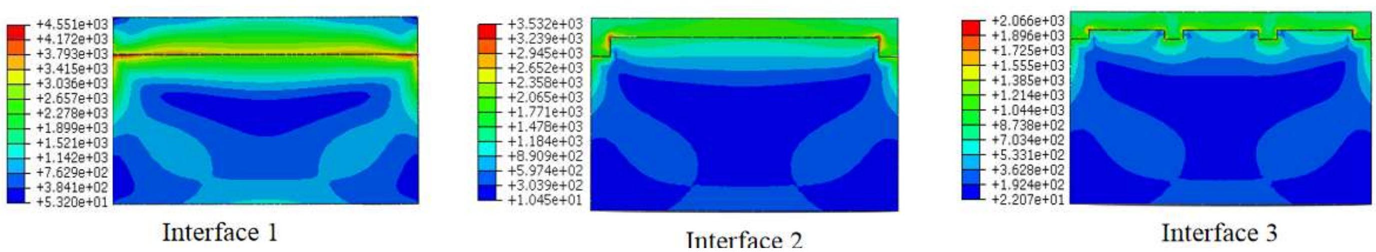


**Figure 7:** The residual stress at different interfaces.

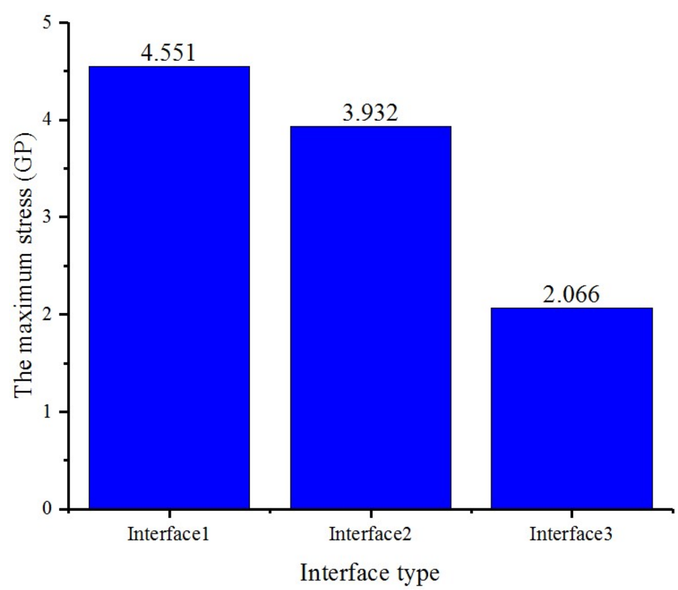


**Figure 8:** The maximum Mises stress values at different interfaces.

and WC. The farther away from the interface, the smaller the cutting tooth stress and the more uniform the distribution. The maximum residual Mises values of several interfaces are shown in Fig. (**8**). The maximum residual Mises stress of plane 1 interface is 4.551 Gpa, and the maximum residual Mises stress occurs in the whole bonding plane. The main reason is that the connection between PCD layer and WC substrate surface is relatively fragile. When the temperature is too high or too low, the shrinkage rate of PCD layer and WC collective material is very different due to the different thermophysical properties, resulting in large stress fluctuation. The maximum Mises stress of No. 2 non-planar interface is located at the plane inflection point, which is fundamentally due to the different thermophysical properties of PCD layer and WC matrix material. The shrinkage rate varies from point to point. At the inflection point, the stress generated during point contact is greater. Multiple piles are used to connect the No. 3 non-planar interface, and the tree stumps are embedded in the interface. Excessive thermal expansion of WC will be limited by PCD layer, which will delay the expansion effect and greatly reduce the diffusion of residual stress. This concave-convex interaction mode can greatly reduce the rapid expansion of residual stress in case of uneven thermal expansion and cold contraction of residual stress.

In conclusion, the non-planar interface not only increases the bonding area between the PCD layer and WC matrix and improves the interfacial bonding force, but also disperses the action area of shear stress when the non-planar interface is subjected to shear stress, improves the shear resistance and increases the service life of the cutter. The combination mode of the non-planar interface is more significant to improve the strength and shear resistance of cutting tooth joint surface. When the PDC tooth interface is designed in the form of a non-planar interface, the performance of the cutter is better.

### 3.3. Study on Comprehensive Stress of Cutter Under Different Interfaces

During the interaction between cutter and rock, the residual stress and cutting stress are affected together. The comprehensive stress analysis of cutting teeth is studied to obtain the failure mechanism of cutting teeth when cutting rock at high temperatures.

Figure (**9**) shows the axial comprehensive stress field of the cutter under different interfaces. The contact area between the tooth edge and the rock under different interfaces is mainly compressive stress, which is due to the extrusion of the cutter by the rock under the force of the rock when the cutter scrape the rock. The maximum axial comprehensive stress of interface 1 is the highest, which is 4.497 Gpa, the axial comprehensive stress of interface 2 is the second, and the axial comprehensive stress of interface 3 is the smallest. The No. 1 plane interface produces an axial high tensile stress region at the tooth surface from the axial comprehensive stress nephogram, which is very easy to crack and break the PCD layer in the axial direction, so as to separate from the matrix. The axial comprehensive stress of No. 2 and No. 3 non-planar interface is smaller when the residual stress and cutting stress act together, and the interface adhesion is stronger. The maximum comprehensive internal stress of the interface occurs near the bonding interface between PCD layer and WC matrix when the cutter scrapes the rock, and the damage is mainly caused by tensile stress, which is mainly due to the continuous temperature rise and cooling of PCD layer near the cutting rock, is caused by uneven expansion of PCD layer material and WC matrix material due to different expansion coefficient. When the tensile stress is large enough, the strength of the bonding part between PCD layer and WC matrix will be reached, and the diamond layer will peel off and fail, as shown in Fig. (**10**).

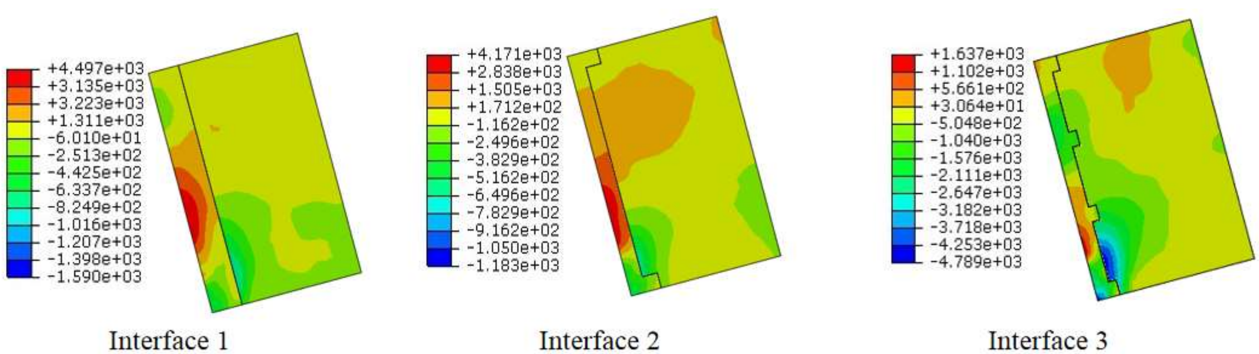


**Figure 9:** The axial comprehensive stress under different interfaces.

Figure (**11**) shows the comprehensive shear stress field of the cutter under different interfaces. The comprehensive shear stress field of plane interface 1 is the smallest, that is, the shear capacity of plane interface 1 is the smallest under the joint action of residual stress and cutting stress, with the minimum value is 822.9 Mpa. The No. 2 and No. 3 non-planar interfaces increase the contact area of the interface, disperse the stress acting on the interface, and improve the bonding strength between the interfaces. When the residual stress and cutting work together, the shear resistance is greatly improved, and the non-planar contact also greatly reduces the impact effect during scraping. Compared with the residual stress, the comprehensive stress of several non-plane shear interfaces is reduced by 13.2% and 5.4% respectively. The maximum comprehensive shear stress of No. 2 and No. 3 non-planar interface is 1.078 Gpa and 2.095 Gpa respectively, that is, the shear capacity is the strongest. The main reason is that the uneven contact of the non-planar interface greatly disperses the stress effect and greatly improves the shear capacity.

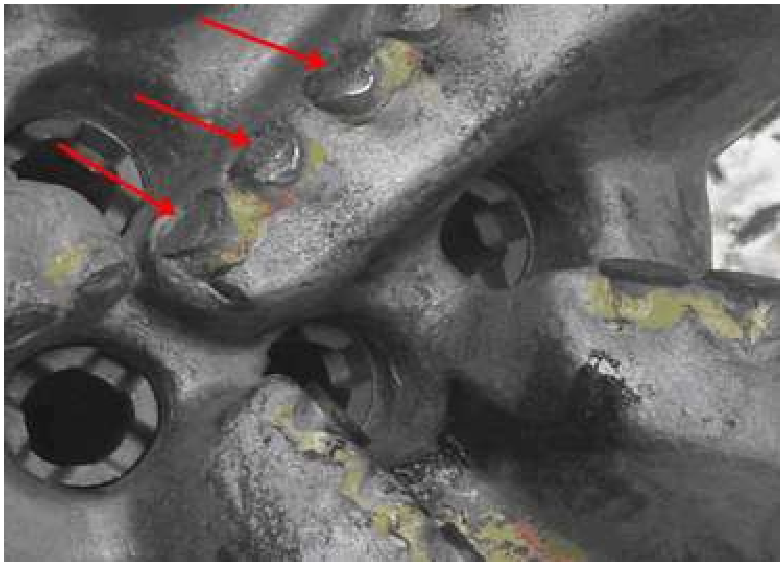

**Figure 10:** The separation of diamond from matrix caused by tensile stress of composite sheet.

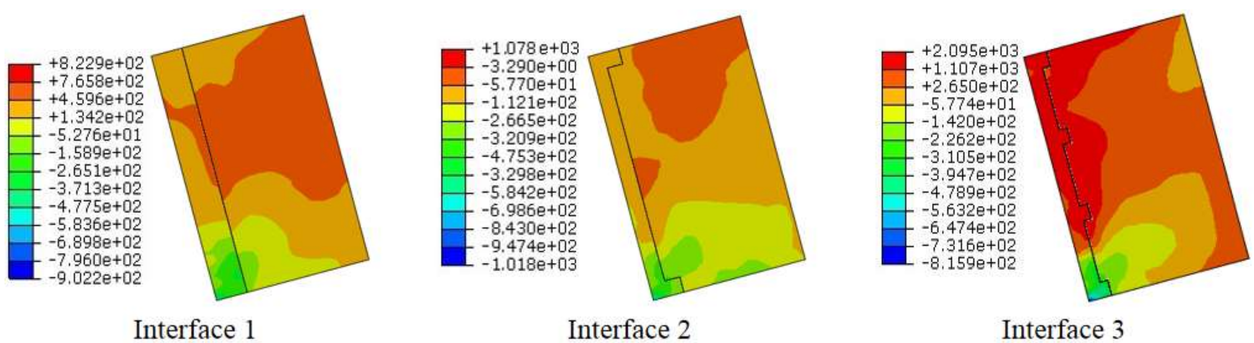


**Figure 11:** The comprehensive shear stress under different interfaces.

Figure (**12**) shows the comprehensive Cpress stress distribution when the cutting tooth scrapes the rock. Under different interfaces, the maximum Cpress stress area is on both sides of the lowest point of the tooth edge, and the whole stress distribution is symmetrically distributed on both sides of the lowest point of the tooth edge. The Cpress stress on the tooth edge of No. 1 plane interface is the largest, with the maximum value of 2.3 Gpa. Under this interface, the amplitude of Cpress stress fluctuates greatly, and the load fluctuates greatly, which is prone to impact failure, resulting in low impact resistance. The stress fluctuation of Cpress under No. 2 interface is relatively small, and the impact resistance is relatively good. The load fluctuation under No. 3 interface is the smallest, and the impact resistance is the highest. The main reason is that at the non-planar contact, the uneven contact interface can greatly disperse the load fluctuation, to greatly improve the impact resistance of the cutter. At the same time, the convex part greatly improves the thickness of the diamond layer on both sides of the cutter, to increase the wear resistance of the composite.

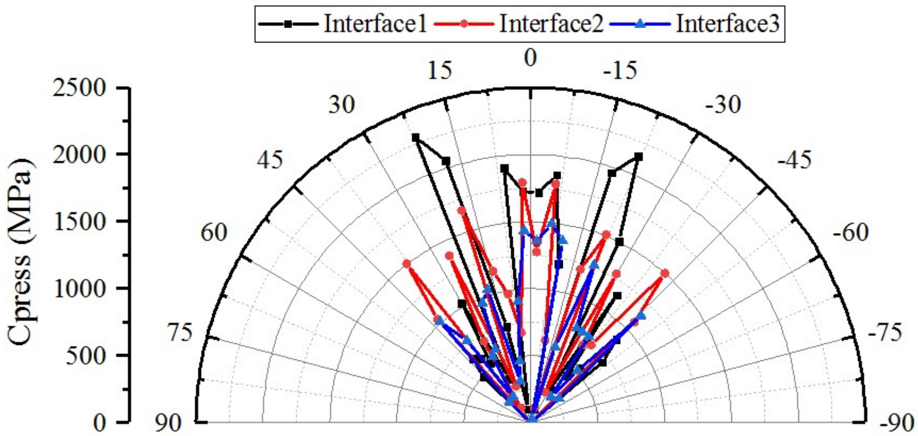


**Figure 12:** The comprehensive Cpress stress of cutter under different interfaces.

In conclusion, for the formation with high hardness and strong abrasiveness, only from the structural form, the selection of non-planar interface is more suitable for the pursuit of impact resistance and wear resistance of cutter, when designing the cutting tooth interface of high-temperature geothermal PDC bit.

## 4. Conclusions

The residual stress of plane interface and non-plane interface, the stress under the joint action of cutting stress and temperature field are studied:

1) The residual stress field and temperature field of the cutter with different interfaces are studied. The non-plane contact interface increases the contact area between interfaces, makes the interface bonding force stronger and the shear resistance higher, which is conducive to resisting the impact of external load and has a good buffer effect on the impact load.

2) Non-planar contact interface can reduce the temperature transfer efficiency and lower the heat transfer temperature, which can improve the high-temperature resistance of the cutter and improve the service life of the cutter.

3) When the residual stress and cutting stress act together, the overall shear strength of the non-planar interface cutter decreases, which are higher than that of the planar interface cutter. The non-planar interface has higher wear resistance and impact resistance under the combined action of residual stress and cutting load, and has a better effect on improving the impact resistance, thermal stability and wear resistance of the composite, which can be used as the choice of the composite interface.

## Conflict of interest

Authors declared that there is no conflict of interest.

## Acknowledgements

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