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Short communication

Effect of different oxides addition on the thermal expansion coefficients and residual stresses of Fe-based diamond composites

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Abstract

CeO_2, La_2O_3, Y_2O_3, and V_2O_5 were added in an Fe-based matrix, and then the matrices were hot pressed at 700 °C. The thermal expansion coefficients and fracture stresses of the matrices were investigated, and residual stresses between the diamonds and matrices were simulated by finite element analysis. The weight losses of the specimens with diamonds were measured using a pin-on-disk wear testing rig. The surfaces from the wear tests were also examined by a scanning electron microscope. Results showed that the residual stress, difference of residual stress from fracture stress and weight loss all decreased after adding Y_2O_3, La_2O_3, V_2O_5, and CeO_2, and the decrement increased in the same order. Among the four oxides, adding V_2O_5 and CeO_2 remarkably improved the diamond retention capacity of the Fe-based matrix.

Keywords: Residual stress; Coefficient of thermal expansion; Diamond tool

1. Introduction

Given the extreme hardness of diamond, it is widely used as an abrasive element for polishing suspensions, as well as for grinding and cutting tools [1]. Four types of bonding systems, i.e., metallic, resinous, electroplated, and vitreous matrices, are used to fix diamond particles [2]. For metallic matrices, diamonds are mixed with metal powders, and the mixtures are sintered with powder metallurgy techniques. Hot pressing is widely used at present in fabricating diamond tools, and the pressure can activate sintering by inducing creep. The diamonds are bound by compression derived from shrinkage upon sintering, and the compressive stress arises from differences between the coefficients of thermal expansion (CTEs) of diamonds and metal matrix augmented by any volume change [3]. The thermal expansion mismatch between diamonds and metal matrix induces residual stress at the interface, which is responsible for retention capability [4]. A previous study has shown that the maximum tensile stress between the diamonds and elastic metal matrix is higher than the fracture stress of the matrix, and cracks are easily generated at the interface. The diamond retention capacity of the matrix decreases, and diamonds are prematurely lost during the cutting action of a diamond tool [5]. Therefore, the decrease in mismatch between elastic metal matrix and diamonds can decrease residual stress and improve the retention capacity of the matrix.

The CTE of diamond is low at room temperature but sharply increases with increased temperature, e.g., 1.0042×10^{-6}/°C at 25 °C and 4.9768×10^{-6}/°C at 1027 °C [6]. For metal matrices, a Co-based matrix has a similar thermal expansion characteristic that can result in good embedding and adherence between diamonds and matrix [7]. Therefore, cobalt powders are widely used to manufacture diamond tools [8]. However, Co is expensive because it is a strategic metal and a suspected carcinogen that necessitates stringent precautions during manufacture and use [9]. Considering all these negative points, numerous studies focus on Fe-based alloys with proper metals aiming at the substituent of the Co-based metal matrix, e.g., Fe–Cu–Co [10,11] and Fe–Ni [12] alloys. Ceramic particles such as SiC [13], CeO_2 [14], and La_2O_3 [15] have been added into Fe-based alloy to improve its mechanical properties. In oxide dispersion-strengthened steels, adding Y_2O_3 improves creep resistance at high temperatures after hot isostatic

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pressing [16]. V_2O_5 is then added to bronze by spark plasma sintering [17].

In this work, Fe–Cu–Co–Ni–Sn alloys added with CeO_2, La_2O_3, Y_2O_3, and V_2O_5 were prepared by hot pressing. The CTEs and fracture stresses of the five matrices with and without oxides were investigated. Residual stresses between the diamonds and matrices were simulated by finite element analysis (FEA). A computational strategy was developed to forecast the residual stresses between the diamonds and matrices with different thermal expansion properties.

2. Experimental procedure

2.1. Specimen fabrication and test methods

The starting metal materials used were <75 μm Fe powder and electrolytic Cu powder, as well as <43 μm Ni, Co, and Sn powders. The starting oxide materials used were 10 μm CeO_2 and La_2O_3 powders, as well as 5 μm V_2O_5 and Y_2O_3 powders. A mixture of Fe–30 wt.%Cu–10 wt.%Co–5 wt.%Ni–5 wt.%Sn composed the Fe-based matrix. 0.5 wt.% CeO_2, La_2O_3, Y_2O_3, and V_2O_5 was added into the Fe-based matrix respectively. The five mixtures were blended for 2 h in a rotary mixer (∞-shape), respectively. The mixtures were hot-pressed in graphite moulds for 2 min at 700 °C [18]. The specimens were rectangular and had dimensions of 25 mm × 5 mm × 5 mm.

CTEs were determined from 700 °C to room temperature (35 °C) using a high-precision thermal mechanical analyser (TMA) at a cooling rate of 10 °C min^{-1}. Data were collected in terms of linear change (LC) with respect to temperature. Fracture stress was measured by a three-point bending test. Diamonds of 170/200 US mesh were added in the five matrices, and the concentration of the diamonds was maintained at 25 vol%. The weight losses of the specimens with diamonds were measured using a pin-on-disk wear testing rig at a sliding speed of 2.18 m s^{-1} for 2 min, according to the method of Venkateswarlu [19]. This test was conducted against a 100 grit emery paper, and the applied load was 1.5 kg. The surfaces from the wear tests were also examined by a scanning electron microscope for microstructure evaluation.

2.2. Finite element modelling

FEA was performed to determine thermal residual stresses in each diamond particle after the cooling stage of the sintering process. Symmetric conditions were used for diamonds embedded in the five matrices. Three-dimensional shapes were modelled with two-dimensional axisymmetric elements, and ANSYS element Vector Quad 13 with eight nodes and reduced integration points was used. The diamond particles were assumed to be isotropic linear elastic with Young's modulus $E=1050$ GPa and Poisson's ratio $\nu=0.2$. Simulation was performed using an elastic model that introduced the mechanical behaviour of the five matrices with Young's modulus $E=185$ GPa and Poisson's ratio $\nu=0.3$. The CTEs of diamonds at different temperatures in Fig. 1 are taken from literature [6], and those of the five matrices were experimentally obtained.

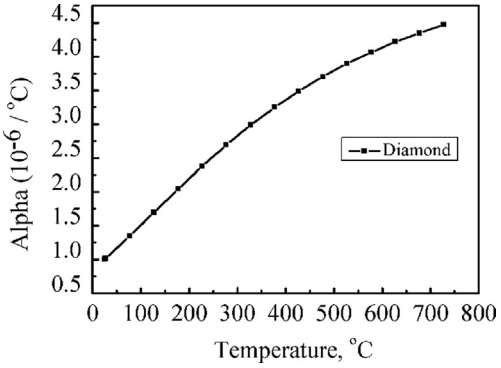

Fig. 1. The linear coefficient of thermal expansion (25–727 °C) of diamond.

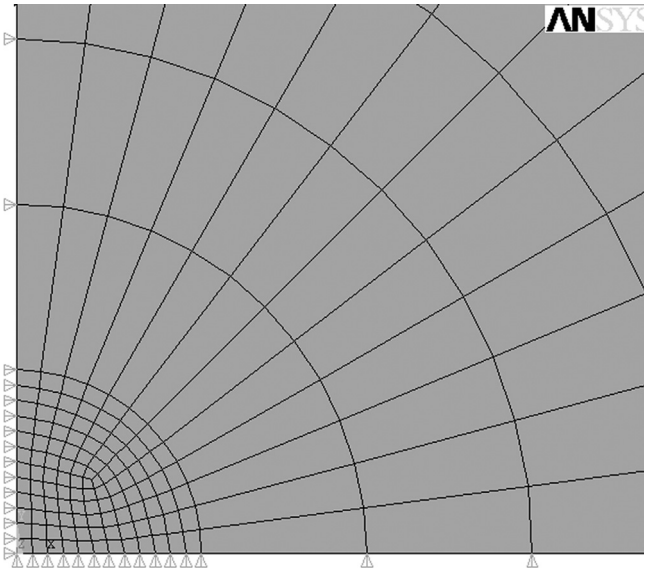

Fig. 2. Finite element model of the numerical analysis.

Fig. 2 presents the mesh used for numerical analysis. Only one quarter of the model was meshed because of symmetric conditions, in which a spherical diamond was surrounded by a spherical Fe-based matrix 10 times greater in size. A fine mesh was used close to the diamond for detailed investigation of residual stress. The nodes on the *x*-direction of the model were not allowed to move in the *y*-direction, and vice versa.

Zero stress of the diamond composites at the maximum hot pressing temperature was assumed. Thermal loads were applied under the assumption that temperature was spatially uniform throughout the composites. The composites were assumed to cool suddenly from the maximum hot pressing temperature to room temperature [20]. Therefore, no time-dependent stress relaxation during cooling was considered. FEA results were obtained, and the stress distribution fields around a diamond particle were visualised.

3. Results and discussion

3.1. Influence of different oxides addition on LC and CTE

The experimentally obtained LCs of the five matrices are shown in Fig. 3. The LCs of all matrices increase with

increased temperature, and the LCs of the matrices with oxides are higher than that of the matrix without oxide. The LC of the matrix with CeO_2 is the lowest among the matrices with oxides, and the LCs of the matrices with V_2O_5, Y_2O_3, and La_2O_3 increase in the same order (Fig. 3b).

The CTEs of the matrices with V_2O_5, Y_2O_3, and La_2O_3 increase with increased temperature, as shown in Fig. 4. The CTEs of the three matrices increase in the same order as their LCs. The CTEs of the Fe-based matrix and the matrix with CeO_2 increase with increased temperatures, except at 450 °C–650 °C.

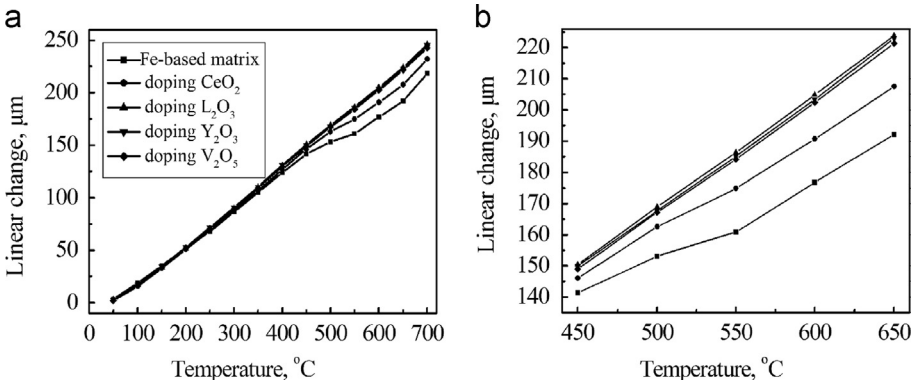

Fig. 3. Linear change of matrices versus temperature (a) 50–700 °C and (b) 450–650 °C.

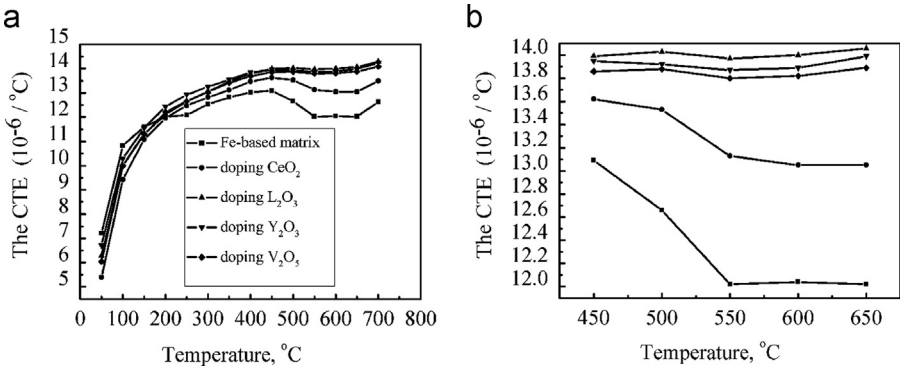

Fig. 4. The linear coefficient of thermal expansion of matrices versus temperature (a) 50–700 °C and (b) 450–650 °C.

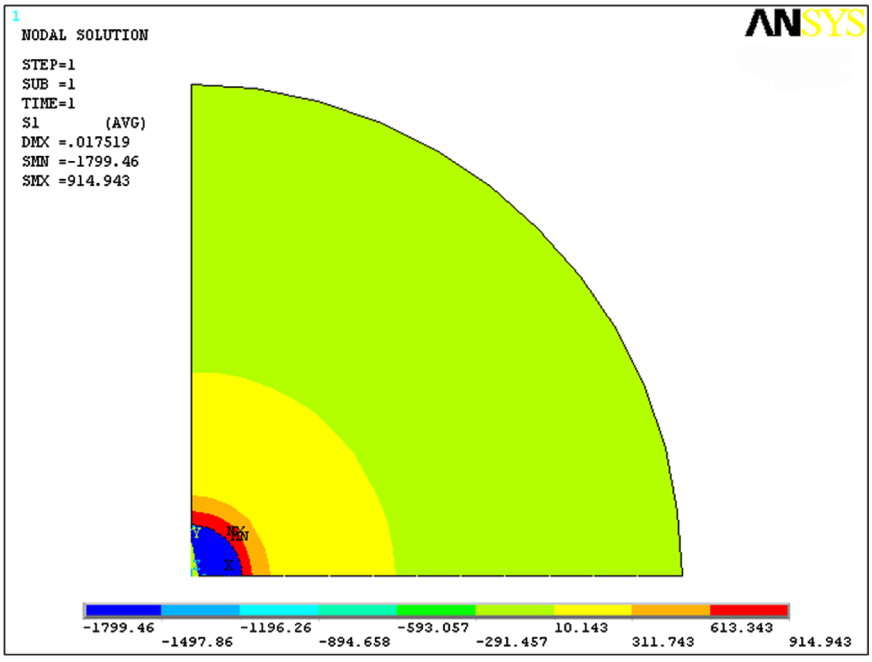

Fig. 5. Residual stress field around the diamond with the Fe-based matrix after hot-pressed at 700 °C.

Within this range, the CTE is an average value, and the increase rate of the LC is relatively low (Fig. 3). By contrast, the CTEs of the matrices with oxides are lower than that of the Fe-based matrix at < 100 °C but higher at 300 °C–700 °C. These results indicate that adding oxides increases the thermal expansion mismatch between the diamonds and Fe-based matrix. The changes in CTE can be attributed to lattice distortion at the interface between the oxide and Fe-based matrix [21], which requires further investigation.

3.2. Influence of different oxides addition on residual stress field

The FEA results of the thermal stress fields of the five matrices are shown in Figs. 5–9. Two kinds of stress distribution exist after cooling, i.e., compressive and tensile stresses. Considering that the CTEs of the five matrices are larger than that of diamond, tensile and compressive stresses appear in the matrices and diamonds, respectively. Furthermore, the maximum tensile

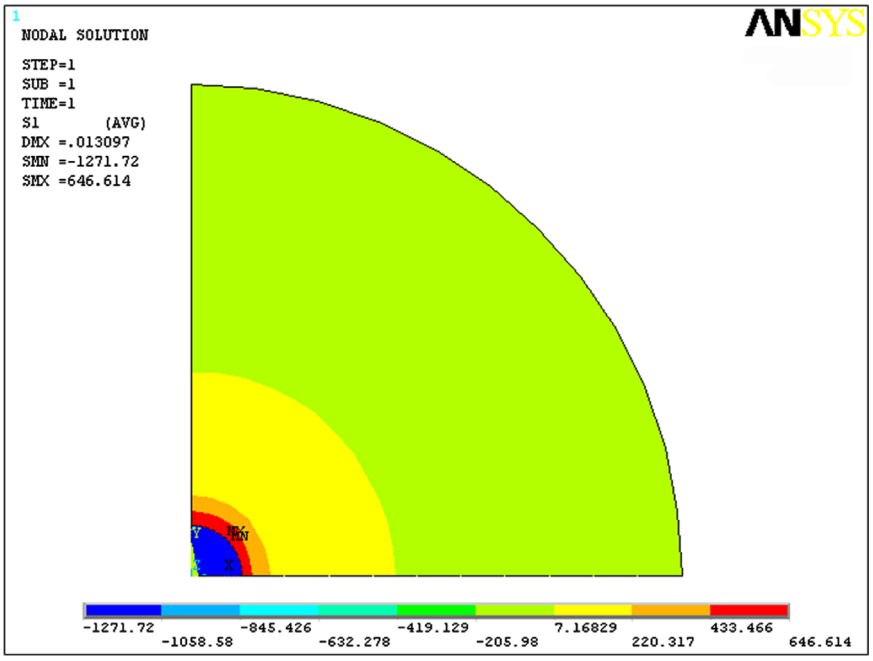

Fig. 6. Residual stress field around the diamond with the Fe-based matrix added CeO_2 after hot-pressed at 700 °C.

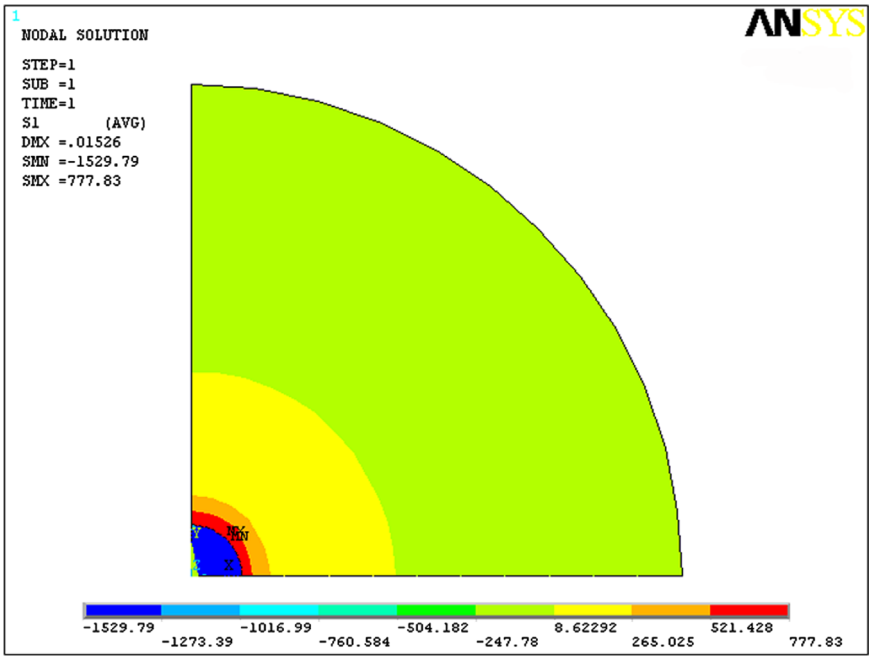

Fig. 7. Residual stress field around the diamond with the Fe-based matrix added L_2O_3 after hot-pressed at 700 °C.

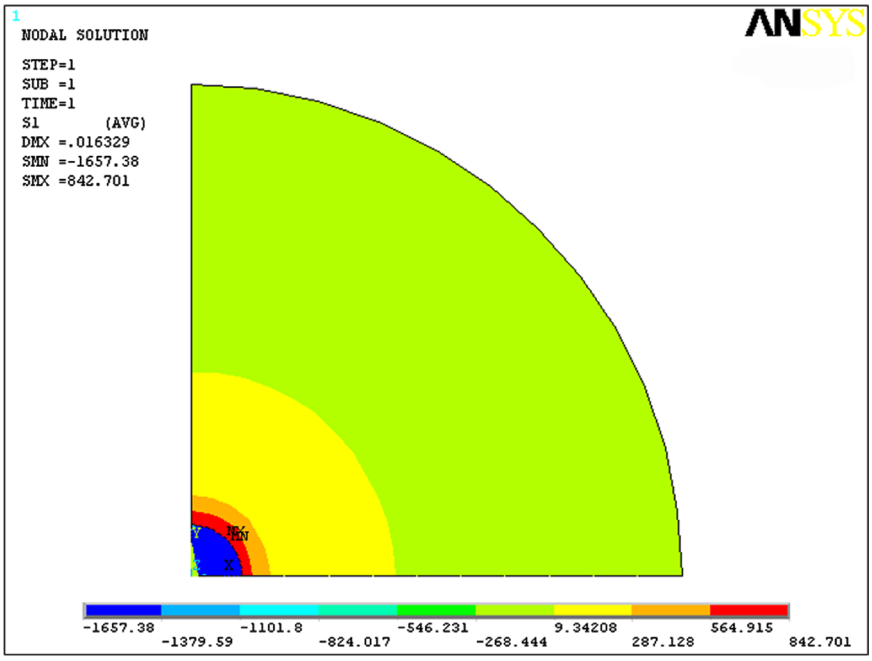

Fig. 8. Residual stress field around the diamond with the Fe-based matrix added Y_2O_3 after hot-pressed at 700 °C.

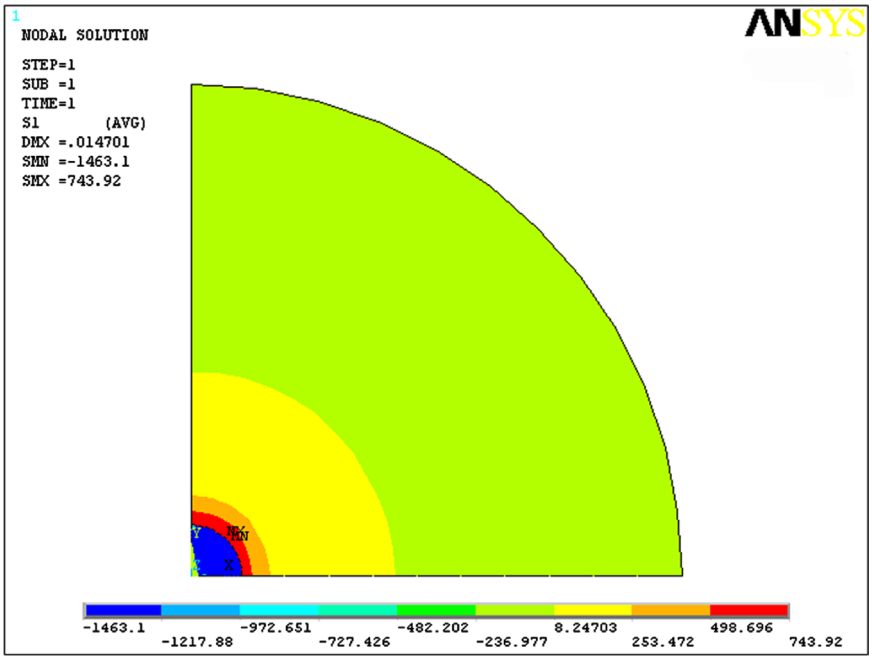

Fig. 9. Residual stress field around the diamond with the Fe-based matrix added V_2O_5 after hot-pressed at 700 °C.

stress is located at the interface, and the tensile stress decreases away from the interface. Compressive stress is constant throughout the entirety of diamond particles.

The maximum tensile residual stress of the Fe-based matrix without oxide is around +914 MPa (Fig. 5), which is close to +970 MPa computed by procedures of ABAQUS in a previous research [5]. However, this residual stress is higher than the fracture stress (Table 1). Therefore, the interface is a potential site for crack initiation under thermal cycling, which may lead to the occurrence of flaws and a decrease in the diamond retention capacity during the cutting action of a diamond tool. After adding CeO_2, La_2O_3, Y_2O_3, and V_2O_5 in the Fe-based matrix, the maximum tensile residual stresses are about +646, +777, +842, and +743 MPa, as shown in Figs. 6–9, respectively. Compared with the Fe-based matrix, the maximum residual stresses of the matrices with oxides decrease by 29% (CeO_2), 15% (La_2O_3), 8% (Y_2O_3), and 19% (V_2O_5). The compressive stresses in the diamond particles

decrease with decreased tensile stress in the matrices. The residual stresses are quite inferior when ceramics are added, because they ease the stress state at the interface of metal matrix–diamonds.

Table 1 shows residual and fracture stresses, as well as their differences among the five matrices. The difference in the Fe-based matrix is the largest, i.e., 405 MPa, and the oxide additions decrease the differences. The differences among matrices follow the order $Y_2O_3 > La_2O_3 > V_2O_5 > CeO_2$. The differences in the matrices with V_2O_5 and CeO_2 reach 91 and 67 MPa, suggesting that adding V_2O_5 and CeO_2 remarkably improves the diamond retention capacity of the Fe-based matrix.

Fig. 10 shows the surfaces of the five matrices obtained by the wear test. Due to the occurrence of the large micro-cracking between the Fe-based matrix and diamond in Fig. 10a, its wear loss is the biggest among the five matrices in Fig. 11. As for the matrix with CeO_2, the contact between the diamond and matrix is the tightest in Fig. 10b, and its wear loss is the smallest among the five matrices. For the other three matrices, the amount of the micro-cracking follow the order $Y_2O_3 > La_2O_3 > V_2O_5$ in Fig. 10c–e, and the weight losses of the three matrices follow the same order in Fig. 11. The results of the weight loss and the microstructure after the wear test confirm the suggestion of improvement in diamonds' retention by adding oxides in the Fe-based matrix.

Table 1
Results residual and fracture stresses, as well as their differences among the five matrices.

Matrix	Residual stress (MPa)	Fracture stress (MPa)	Residual stress − fracture stress(MPa)
Fe-based matrix	914	509	405
Adding CeO_2	646	579	67
Adding La_2O_3	777	536	241
Adding Y_2O_3	842	513	329
Adding V_2O_5	743	652	91

4. Conclusions

The CTEs and residual stresses of Fe-based matrices with oxides were studied by experimental and FEA. Adding CeO_2, La_2O_3, Y_2O_3, and V_2O_5 obviously affected the CTE and residual stress between the diamonds and matrices. The following conclusions were drawn.

(1) The CTEs of matrices with V_2O_5, Y_2O_3, and La_2O_3 increased with increased temperature, and the CTEs of the three matrices increased in the same order. The CTEs of the Fe-based matrix and the matrix with CeO_2 increased with increased temperature, except at 450 °C–650 °C.

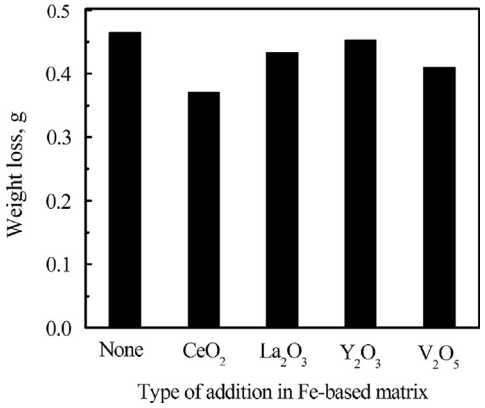

Fig. 11. Weight loss of different specimens after the wear tests.

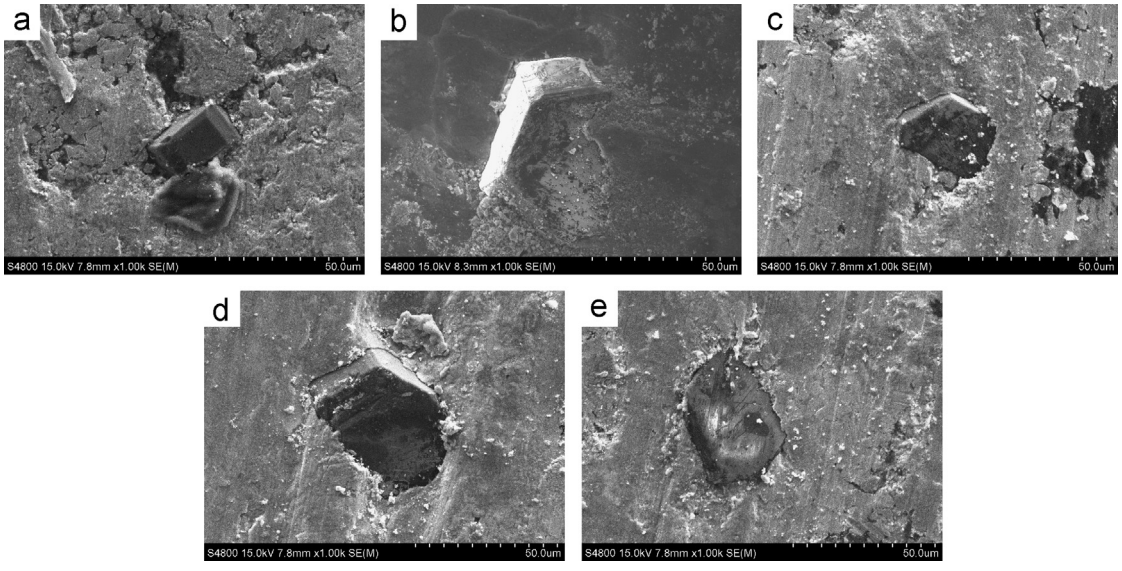

Fig. 10. Microstructures from the wear tests (a) Fe-based matrix, (b) Fe-based matrix added CeO_2, (c) Fe-based matrix added L_2O_3, (d) Fe-based matrix added Y_2O_3 and (e) Fe-based matrix added V_2O_5 respectively.

(2) The residual stress, difference of residual stress from fracture stress and weight loss all decreased after adding Y_2O_3, La_2O_3, V_2O_5, and CeO_2, and the decrement increased in the same order.

Among the four oxides, adding V_2O_5 and CeO_2 remarkably improved the diamond retention capacity of the Fe-based matrix.

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