Abstract: Residual stresses’ magnitude generated by deposition, quenching stress, thermal stress operation temperature, and infiltration in the thermal barrier coating (TBC) of gas turbines was determined. A thermal barrier coating was manufactured by the deposition of two layers, CoNiCrAlY and yttria-stabilized zirconia (YSZ), on an AISI 304 stainless steel substrate. The CoNiCrAlY was deposited by using an HVOF gun and the YSZ by an atmospheric plasma spray (APS). The TBCs were heat-treated at 1250 °C, with a CMAS (CaO, MgO, Al₂O₃, and SiO₂) attack with a concentration of 10 mg/cm² for 6 h in order to evaluate the evolution of the state of residual stresses in the coating at a high temperature. Residual stresses were determined by employing the modified layer removal method for duplex coatings (MLRMD), ANSYS Version R19.2, and the equations proposed by Noda et al. In the YSZ, the total maximum residual stresses were 139 MPa in compression, and in the CoNiCrAlY, the maximum residual stress was 214 MPa in compression. The factor that has the largest effect on the magnitude of residual stresses was the infiltration of the CMAS in the YSZ.

Keywords: thermal barrier coating (TBC); residual stresses; thermal spraying

1. Introduction

A thermal barrier coating (TBC) protects a softer material, usually a substrate. This substrate is protected against oxidation, corrosion, and heat transfer. The heat transfer is due to the combustion process in a closed chamber that emits gases through the protected blades of a turbine used as a substrate [1]. Typically, a TBC is a couple of coatings deposited in a substrate. The first one is named the top coat (TC) of ceramic material, and the last one is called the bond coat (BC) of metallic alloy. Typically, the TC is a compound of stabilized zirconia with yttrium (YSZ), and the BC is an alloy of MCrAlY (M = Ni + Co, Ni, or Co).

The YSZ is the most applied material in TBCs due to its thermal properties, low thermal conductivity, thermal shock resistance, and low coefficient of thermal expansion [2]. The particles of this powder are spherical although some are slightly deformed. The spherical geometry ensures good flow through the powder feed system [3]. The CoNiCrAlY (BC) promotes good adhesion between the YSZ (TC) and the substrate because its thermal expansion coefficient is similar [4]. In addition, the BC protects against oxidation and hot corrosion [5]. To produce TBCs, thermal spraying methods are used because they are cheaper and take a low manufacturing time [6]. In the last decade, several researchers [7–9] have shown that some residual stresses are generated during the deposition of thermal barrier coatings (TBC). These stresses affect the physical properties of the coating and
reduce the lifetime of the component that covers it. For this reason, the characterization of these stresses and their reduction are paramount for the researchers. According to Widjaja et al. [9], residual stresses generated during the deposition in TBCs using the plasma thermal spray technique are due to some physical phenomenon, such as phase transformation, sudden splatter shrinkage, and a mismatch between the thermal expansion coefficients of the substrate and the coating.

Atmospheric plasma spray (APS) projects molten particles at a low speed. In this process, the gun has a copper-tipped tungsten cathode and an annular copper anode, which are cooled by water flowing in an internal circuit. A high electric voltage arc is generated between cathodes. When gases are passed in this high potential, the gases are ionized by raising the temperature and producing the plasma [10]. Ionization is obtained due to collisions between the neutral gas molecules and an interaction with the electric arc. The plasma protrudes from the space between the flame-shaped electrodes at the exit of the gun. The feed material in these systems is dust that is quantified and fed directly into the plasma flame. Upon contact with the plasma, powders absorb thermal and kinetic energy and project into the substrate. The APS can reach a gas temperature of 12,000 to 16,000 °C [10], making it possible to melt ceramic materials. The high velocity oxygen fuel (HVOF) sends molten and semi-molten particles at a high speed and low temperature. This deposition technique uses a flame to heat the material, which is obtained from the combustion of oxygen and combustible gas. This material (generally in the form of powder) absorbs thermal energy and is then driven towards the substrate with the aid of compressed air, reaching supersonic speeds of gas and particles [11]. In both methods, the impact of the particles on the substrate generates residual compressive stresses [12], which reduce the tensile stresses that eventually cause the delamination of a coating in operation [13]. Experimental studies have shown that residual compressive stresses can increase components’ efficiency [14].

The improvement in the technology of the deposition of TBC can lead to gas turbines operating at high temperatures (1200 °C, approximately), greater efficiency, and higher performance of fuel consumption [15], which decreased the generation of greenhouse gases [16]; however, due to the high temperatures the turbines operate, the TBCs are exposed to thermal and mechanical loads. Additionally, the TBCs are susceptible to degradation due to the molten oxides of calcium, magnesium, aluminum, and silicon (CMAS). This CMAS results from the ingestion of siliceous mineral wastes (dust, sand, ashes) that come to the turbine from the combustion camera [17]. When the hot gases from the combustion camera come to the turbine with a temperature of about 1200 °C, the CMAS melts and infiltrates into the TBC. This infiltration generates a mechanism of the detachment of the TBC [18] that raises the liberation of energy and modifies the TBC’s mechanical properties. Furthermore, the difference on the thermal expansion coefficient between the CMAS and the TBC causes thermal stresses during the cooling at room temperature [19], which makes the TBC susceptible to the mechanisms of cracking and delamination [20,21]. APS flash bond coatings deposited on a dense high velocity oxy-fuel (HVOF) bond coating have been shown to exhibit longer thermal barrier coating (TBC) lifetimes during 100 h of furnace cycle testing [22]. In this work, flash bond coating was not used because the heat treatment cycle was 6 h. In addition, in the manufacturing process of the TBC, a state of compression stresses developed in the substrate when its surface was prepared using shot blasting for the deposition of the BC. When the BC was deposited, tensile stresses generated due to the splat’s rapid cooling that reached the substrate [2]. In addition, a residual compression stress generated in the TC because its thermal expansion coefficient was smaller than the substrate. Meanwhile, in the BC, tensile stresses were generated [23]. When the turbine is operating at a high temperature, a state of compressive stresses is generated [3], and CMAS infiltration also generates residual stresses. The electrophoretic deposition (EPD) process of the polyaniline (PANI) technique allows a better control in the deposition of the coating [24,25], avoiding or reducing its porosities and increasing its protection against corrosion [26].
During the last decade, different techniques have been proposed to study the final stress state of TBCs that are produced by thermal spraying: X-ray diffraction [27], indentation [28], material removal [29], and the finite element method [30]. Zhu et al. [31] simulated the thermal cycling process of TBCs and analyzed the stress state. Rajabi et al. [32] simulated residual stress distribution in a thick thermal barrier coating. Abdelgawad and Al-Athel [33] investigated the effect of TC surface roughness and pores on the developed residual stresses during thermal cycling to different TGO thicknesses. Ahmad et al. [34] determined residual stress through the thickness by a finite element. However, there is no work that shows all the stages that generate residual stresses in the TBC from its manufacture to its startup. The magnitude of the TBC residual stresses profile is determined in the current investigation. These stresses are due to the rapid cooling of the drops sprayed by the plasma (quenching stress), the difference in the thermal expansion coefficient (thermal stress) between the BC and the TC, the operating temperature of the gas turbines (1250 °C), and the CMAS infiltration for 6 h of operation, using the MRCMRB technique [35], Noda et al. [36] equations, and ANSYS software. The Noda et al. equations were performed to calculate the residual stresses due to the difference between the thermal expansion coefficients of the TC, BC, and substrate (thermal stress). ANSYS software and the MRCMRB technique were used to determine the residual stresses due to the high temperature operation of the TBC.

2. Materials and Methods

2.1. TBC Deposition

TBCs (Figure 1) were deposited on stainless steel AISI 304 substrates, 25.4 mm × 25.4 mm × 6.35 mm in size. The BC and TC were obtained by the deposition of powders of a CoNiCrAlY alloy (AMDRY 9954, Co32Ni21Cr8Al0.5Y) and yttria-stabilized zirconia (NS-204, YSZ), respectively, both from Sulzer Metco. Before deposition, the substrates were cleaned with acetone and grit blasted by an air stream carrying alumina particles that impacted at a 45° angle and at a distance of 200 mm. They were then recleaned with acetone; the surface roughness (Ra) ranged from 3 to 7 µm. The BC was deposited by a HVOF system, model DJH2700 by Sulzer, with a powder feed rate of 38 g/min and a distance of 203 mm. The mean thickness of this layer was 250 ± 5 µm. For each layer, 16 passes were applied using a gun lateral displacement speed of 1.5 m/s. Table 1 shows the pressures (bar) and flow rates (SLPM, standard liters per minute) of the gases employed.

![Figure 1. Thermal barrier coating (TBC) system.](image-url)
### Table 1. Pressure and flow rate of the gases.

|          | HVOF          |           |
|----------|---------------|------------|
| Pressure (bar) Flow (SLPM) | Oxygen 10 154 | Propane 8.9 38 |
|          | Air 6.8 294   |            |
|          | APS Pressure (bar) Flow (SLPM) | Argon 5.2 42 |
|          | Hydrogen 3.4 7 |            |

#### 2.2. Thermal Treatment of the Coatings with CMAS Attack in TBCs

After the thermal treatment of the TBCs, differential scanning calorimetry was performed on the CMAS (mordenite) to determine its melting temperature. The magnitude of this observed temperature was approximately 1250 °C.

After depositing the TBC on the stainless steel substrate AISI 304, the thermal treatment of the TBCs was realized in a tubular furnace SWGL-1600x at a temperature of 1250 °C with a CMAS attack of 10 mg/cm² on the TBC surface. The heating rate was 10 °C/min to reach a temperature of 1250 °C, and the cooling ramp was 6 °C/min with a vacuum of 1.33 × 10⁻⁸ bar. The chemical composition of the mordenite is shown in Table 2.

#### Table 2. CMAS chemical composition (mordenite).

| Composition | SiO₂ | Al₂O₃ | MgO | CaO | Na₂O | K₂O | H₂O⁺ | H₂O⁻ |
|-------------|------|-------|-----|-----|------|-----|------|------|
| % mol.      | 66.06| 12.32 | 0.36| 3.02| 3.86 | 0.50| 9.19 | 4.68 |

#### 2.3. Residual Stress Determination

To calculate the residual stresses on the coatings, the physical properties of the materials were used (AISI 304, BC (CoNiCrAlY), and y TC (YSZ), as shown in Table 3.

#### Table 3. Physical properties of the TBC materials.

| Property                        | CoNiCrAlY [37] | YSZ [7] | AISI-304 [38] | CMAS [39] | TGO [7] |
|---------------------------------|----------------|--------|---------------|-----------|--------|
| Young modulus (GPa)             | 200            | 70     | 200           | 84.3      | 380    |
| Poisson coefficient             | 0.30           | 0.23   | 0.29          | 0.26      | 0.25   |
| Coefficient of thermal expansion (10⁻⁶ °C) | 13.6 | 8.6   | 17.3 [40]    | 9.32      | 5.4    |
| Thermal conductivity (W/mK)     | 25             | 2.17   | 15.9          | -         | -      |

The residual stress profile in the TBCs was determined by the MRCMRB technique [35], Noda et al. equations [36], and ANSYS software. According to the method modified by Yañez et al. [35], the mathematical analysis of the stress was performed using the following equation:

\[
\epsilon_x = \epsilon_{x0} + k_{xz} \epsilon_y = \epsilon_{y0} + k_{yz}
\]  

(1)

where \( k_{xz} \) and \( k_{yz} \) are sample curvatures. For a plain stress state, the stress-deformation equation is given by the following:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\end{bmatrix} = E\frac{1}{1-v}\begin{bmatrix} 1 & v \\ v & 1 \end{bmatrix} \begin{bmatrix}
\epsilon_x \\
\epsilon_y \\
\end{bmatrix}
\]

(2)
where $E'$ is a relationship that involves the Young modulus, $v$ is the Poisson ratio of the materials, $E_s$ is the Young modulus of the substrate, $E_{BC}$ of the BC, and $E_{TC}$ of the TC:

$$E_i = \frac{E_s}{(1 - v_s)} E_{BC} = \frac{E_{BC}}{(1 - v_{BC})} y E_{TC} = \frac{E_{TC}}{(1 - v_{TC})}$$  \hspace{1cm} (3)

where $E_i$ is the overall Young modulus of the TBC:

$$E_i = E_{BC} + E_{TC}$$  \hspace{1cm} (4)

If $\sum h \geq h_{TC}$, then $E_{TC} = 0$, but if $\sum h \geq h_{TC} + h_{BC}$, then $E_{TC} = E_{BC} = 0$.

The Noda et al. [28] equations were taken to determine residual stresses due to the difference between thermal expansion coefficients between the TC, BC, and substrate (thermal stress), as shown below.

$$\sigma_i = \frac{E_i}{D} \left[ (a_1 T_1 - a_1 T_i) E_i^2 + (a_2 T_2 - a_1 T_i) E_i^2 + 7(a_1 T_1 - a_2 T_1 - 2a_1 T_i) E_1 E_2 - 12 \frac{y}{h} E_1 E_2 (a_1 T_1 - a_2 T_1) \right]$$ \hspace{1cm} (5)

where

$$D = (E_1 + E_2)^2 + 12 E_1 E_2$$  \hspace{1cm} (6)

Equation (5) is reduced to the following:

$$\sigma_a = \frac{E_a E_d}{D} \left[ (a_d - a_s) \left( 7E_d + E_a + 12 \frac{y}{h} E_d \right) T \right]$$  \hspace{1cm} (7)

$$\sigma_s = \frac{-E_a E_d}{D} \left[ (a_d - a_s) \left( 7E_d + E_s - 12 \frac{y}{h} E_d \right) T \right]$$  \hspace{1cm} (8)

where $\sigma_s$ is the residual stress of the BC; $E_a$ and $a_s$ are Young’s modulus and the coefficient of thermal expansion of the BC, respectively. $\sigma_a$ is the residual stress of the TC; $E_a$ and $a_a$ are Young’s modulus and the coefficient of thermal expansion of the TC, respectively. The thickness of the coating $h$ is the total thickness of the coated sample; $T$ is the deposition temperature of the coating.

A study was carried out using the ANSYS software to determine stresses through the finite element method (FEM). First, the components were modeled using SolidWorks software; the model was imported into ANSYS. Figure 2a shows an isometric view of the model. The simulation determined the stresses generated in the ceramic layer (YSZ) and the metal layer (CoNiCrAlY) validated the results obtained experimentally when the TBCs are subjected to turbine operating temperatures. The material was exposed to a temperature of 1250 °C. In the meshing (Figure 2b), shell elements were used for the ceramic and metallic coatings and solid elements (hexahedral) for the substrate. A total of 1099 elements with 5853 nodes were used for the substrate and 2250 elements with 17,280 nodes for both coatings.

![Figure 2. (a) TBC model in ANSYS and (b) meshing.](image-url)
3. Results and Discussion

Figure 3 shows the residual stresses caused by the deposition of the coating (\(\sigma_D\)), (b) quenching stress (\(\sigma_Q\)), and (c) thermal stress (\(\sigma_{TH}\)) [27]. It should be mentioned that in the determination of residual stresses caused by deposition (\(\sigma_D\)) of the TC by APS, only the stresses caused by quenching stress (\(\sigma_Q\)) and thermal stress (\(\sigma_{TH}\)) were considered. Shot blasting produced by APS is negligible due to the low-impact velocity. Figure 3 shows the residual profile of the quenching stress and thermal stress values from 80 MPa to 100 MPa. Quenching stress generated tension residual stresses, and thermal stress generated compressive residual stresses. The sum of the stresses caused by quenching stress and thermal stress results in the stresses due to deposition; values close to zero are observed, similar to those reported by Weyant et al. [3]. In the case of BC deposited by HVOF, the residual stresses caused by the deposition (\(\sigma_D\)), quenching stress and shot blasting (\(\sigma_Q\)), and thermal stress (\(\sigma_{TH}\)) were considered. In Figure 3, tension residual stress values from 248 MPa to 239 MPa, due to thermal stress, and compressive residual stress values from 229 MPa to 217 MPa, due to quenching stress and shot peening, were observed. In the BC, tension residual stress values from 19 MPa to 23 MPa are observed. This behavior is similar to that reported by Lima et al. [29].

![Figure 3. Residual stress caused by TBC deposition.](image)

Figure 4 shows the residual stress profile caused by the operating temperature of the gas turbine, and compressive stress can be observed along with the depth of the TC. The stress increases from 1 MPa at 15 µm from the surface to a maximum of 20 MPa. In the BC, the magnitude of the stress is increased up to a maximum of 65 MPa. A decrease to 45 MPa is observed when approaching the substrate, and an increase of 66 MPa in compressive stress can be observed when reaching the interface with the substrate. This result agrees with that observed by Khan et al. [27]. They concluded that a TBC exposed to high temperatures generates compressive residual stress due to cooling. This can be attributed to the hardness increasing due to the phenomenon of densification because of the thermal treatment, where the material is compacted, and the particles joining together, eliminating the porosities, generating residual stress relaxation, and resulting in a compressive residual stress state [18,41,42].

To validate the results of Figure 4, a study was carried out to determine stresses through FEM using the ANSYS software. Figures 5 and 6 show the residual stress profile caused by the operating temperature of the gas turbine, and compressive stress can be observed along with the depth of the TC, similar to the stresses obtained experimentally. The stresses obtained by simulation are between 18 and 19 MPa (Figure 5), and those obtained experimentally reach a maximum of 20 MPa (Figure 4).
Figure 4 shows the residual stress profile caused by the operating temperature of the gas turbine, and compressive stress can be observed along with the depth of the TC. The stress increases from 1 MPa at 15 µm from the surface to a maximum of 20 MPa. In the BC, the magnitude of the stress is increased up to a maximum of 65 MPa. A decrease to 45 MPa is observed when approaching the substrate, and an increase of 66 MPa in compressive stress can be observed when reaching the interface with the substrate. This result agrees with that observed by Khan et al. [27]. They concluded that a TBC exposed to high temperatures generates compressive residual stress due to cooling. This can be attributed to the hardness increasing due to the phenomenon of densification because of the thermal treatment, where the material is compacted, and the particles joining together, eliminating the porosities, generating residual stress relaxation, and resulting in a compressive residual stress state [18,41,42].

Figure 4. Residual stress is caused by the gas turbine operating the temperature.

To validate the results of Figure 4, a study was carried out to determine stresses through FEM using the ANSYS software. Figures 5 and 6 show the residual stress profile caused by the operating temperature of the gas turbine, and compressive stress can be observed along with the depth of the TC, similar to the stresses obtained experimentally. The stresses obtained by simulation are between 18 and 19 MPa (Figure 5), and those obtained experimentally reach a maximum of 20 MPa (Figure 4).

Figure 5. Residual stress profile in the TC: (a) 50 µm, (b) 100 µm, (c) 150 µm, (d) 200 µm, and (e) 250 µm.
Figure 6. Residual stress profile in the BC: (a) 310 µm, (b) 370 µm, (c) 430 µm, (d) 490 µm y, and (e) 550 µm.

Figure 6 shows the residual stress profile obtained by the finite element simulation (ANSYS Software); in the BC, the residual stresses profile is between 66 and 69 MPa. This result is similar to the result obtained experimentally, which reaches a maximum of 65 MPa (Figure 4).

Figure 7 shows the residual stress profile as blue square dots, due to CMAS infiltration and determined by MRCMRB. In the TC, approximately 15 µm from the surface, the stresses are about 6 MPa in compression; residual stresses increase in magnitude until reaching a maximum of 120 MPa. Approaching the interface with the BC, the magnitude of the stresses decreases slightly in compression; when entering the BC, the magnitude of the stresses increases up to 134 MPa. After that point, a gradual increase is observed up to a maximum of 229 MPa. When approaching the substrate, a decrease to 181 MPa is observed, and when reaching the interface with the substrate, an increase in compressive stress (192 MPa) can be observed. In addition, the relationship between the residual stress profile and the counts per second (CPS) of the concentration of the elements is shown. In the TC, it can be observed that the concentration of zirconium is possibly related to the increase or decrease of the residual stresses. Figure 7 it shows the infiltration depth is also related to the residual stresses. The residual stress increases linearly when the zirconium is maintained at a similar concentration, and between 260 µm and 300 µm depth, there is a small decrease in zirconium, which keeps the residual stress constant.
The compressive residual stresses’ increase could also be attributed to the thickness of the thermally grown oxide (TGO) [42]. Wang et al. [43] and Ahrens et al. [44] comment in their research paper that the residual stress distribution depends on the thickness of the TGO. Additionally, CMAS infiltration leads to accelerated sintering of the YSZ layer, causes shrinkage and increases the Young’s modulus of the YSZ, lowers its deformation capacity, and increases compressive residual stresses in the YSZ layer [45].

Figure 8 shows the total residual stress profile ($\sigma_T$), which is the sum of the residual stresses caused by the deposition of the coating ($\sigma_D$), the stresses generated by the rapid cooling of the droplets sprayed by the plasma (quenching stress, $\sigma_Q$), residual stresses caused by the difference in coefficients of thermal expansion (thermal stress, $\sigma_{TH}$), stresses due to the operating temperature of gas turbines ($\sigma_{OT}$), and the stresses due to the CMAS infiltration in the TC ($\sigma_{CMAS}$). The TC shows that approximately 15 µm from the surface, the stresses are about 6 MPa in compression, and residual stresses increase in magnitude until reaching 139 MPa; entering the BC increases the magnitude of the stress up to 159 MPa. Then, a gradual increase is observed up to 263 MPa, and when approaching the substrate, a decrease to 214 MPa is observed. In Figure 8, it can be seen that the factor that most influences the total magnitude of the residual stresses are the infiltration of CMAS in the TC.

![Figure 7. Residual stress caused by CMAS infiltration.](image)

![Figure 8. Total residual stress in TBC.](image)
4. Conclusions

The residual stress profile of the TBCs, deposited by HVOF and APS and subjected to a high temperature (1250 °C) and CMAS attack for 6 h, were obtained due to quenching stress, thermal stress, the operating temperature of the gas turbines (1250 °C), and CMAS infiltration in the TC; using the MRCMRB experimental technique, ANSYS software, and the Noda et al. equations, the following were concluded:

(a) It was observed that the residual stresses caused by the deposition in the TC are almost neutral because the magnitude of the residual stresses caused by the quenching stress and the magnitude of the compression stresses caused by thermal stress are very similar. The results are consistent with the literature. In the BC, it was observed that the residual tensile stress resulting from the deposition process is because the stress caused by the quenching stress is greater than the stress caused by the thermal stress.

(b) It was observed that after the thermal treatment of the TBC at the operating temperature (1250 °C), compressive residual stresses were generated due to the relaxation of the cooling residual stresses. From Figure 7, it can be observed that the concentration of zirconium is possibly related to the increase or decrease of the residual stresses.

(c) In this work, the magnitude of the residual stress profile of the TBC due to the rapid cooling of the drops sprayed by the plasma was determined (quenching stress); it was due to the difference in the coefficient of thermal expansion between the BC and TC, the operating temperature of gas turbines (1250 °C), and the infiltration of CMAS in the TC during 6 h of operation.

(d) The total maximum residual stress reached in the top coat was 139 MPa in compression, and in the bond coat, the maximum residual stress was 214 MPa in compression.

Author Contributions: Conceptualization, P.Y.-C.; methodology, P.Y.-C.; software, P.Y.-C. and F.J.S.-B.; validation, P.Y.-C., M.L.-R. and J.M.M.-F.; formal analysis, P.Y.-C. and J.A.J.-G.; investigation, P.Y.-C. and V.G.-A.; resources, P.Y.-C.; writing—original draft preparation, P.Y.-C. and M.L.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data underlying the results presented in this letter are not publicly available but may be obtained from the authors upon reasonable request.

Acknowledgments: The authors gratefully thank Universidad Politécnica de Guanajuato, CIATEQ A. C, CICATA-IPN and Tecnológico Nacional de México en Celaya for providing the facilities to perform the experimental work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Habibi, M.; Wang, L.; Guo, S. Evolution of hot corrosion resistance of YSZ, Gd₂Zr₂O₇, and Gd₂Zr₂O₇ + YSZ composite thermal barrier coatings in Na₂SO₄ + V₂O₅ at 1050 °C. J. Eur. Ceram. Soc. 2012, 32, 1635–1642. [CrossRef]
2. Rajendran, R. Gas turbine coatings—An overview. Eng. Fail. Anal. 2012, 26, 355–369. [CrossRef]
3. Weyant, C.M.; Almer, J.; Faber, K.T. Through-thickness determination of phase composition and residual stresses in thermal barrier coatings using high-energy X-rays. Acta Mater. 2010, 58, 943–951. [CrossRef]
4. Jang, H.-J.; Park, D.-H.; Jung, Y.-G.; Jang, J.-C.; Choi, S.-C.; Paik, U. Mechanical characterization and thermal behavior of HVOF-sprayed bond coat in thermal barrier coatings (TBCs). Surf. Coat. Technol. 2006, 200, 4355–4362. [CrossRef]
5. Zhao, L.; Lugscheider, E. High velocity oxy-fuel spraying of a NiCoCrAlY and an intermetallic NiAl-TaCr alloy. Surf. Coat. Technol. 2002, 149, 230–235. [CrossRef]
6. Gómez-García, J.; Poza, P.; Utrilla, Y.V. Crecimiento y caracterización de recubrimientos cerámicos con aplicaciones como barreras térmicas. Cerámica Y Vidrio 2006, 45, 70–74. Available online: http://ceramicayvidrio.revistas.csic.es (accessed on 9 December 2014). [CrossRef]
7. Guo, F.; Zhou, R.; Shang, Y.; Zhang, H.; Pei, Y.; Li, S.; Gong, S. Development of deposition beam current dependent microstructure and nanomechanical properties in ZrO$_2$-8wt% Y$_2$O$_3$ thermal barrier coatings produced by electron beam-physical vapor deposition technique. *Mater. Chem. Phys.* **2021**, *272*, 124998. [CrossRef]

8. Riyadi, T.W.B.; Setiadhi, D.; Anggono, A.D.; Siswanto, W.A.; Al-Kayiem, H.H. Analysis of mechanical and thermal stresses due to TiN coating of Fe substrate by physical vapor deposition. *Forces Mech.* **2021**, *4*, 100042. [CrossRef]

9. Widjaja, S.; Limarga, A.M.; Yip, T.H. Modeling of residual stresses in a plasma-sprayed zirconia/alumina functionally graded-thermal barrier coating. *Thin Solid Films* **2003**, *434*, 216–227. [CrossRef]

10. Metco, S. *HVOF Solutions, Advanced Technology Solutions and Service*. HVOF Solutions, Advanced Technology Solutions and Service: Querétaro, Mexico, 2010.

11. Sulzer Metco, S. An Introduction to Thermal Spray. 2013. Available online: https://silo.tips/download/an-introduction-to-thermal-spray-sulzer-metco (accessed on 1 July 2022).

12. Bansal, P.; Shipway, P.; Leen, S. Residual stresses in high-velocity oxy-fuel thermally sprayed coatings—Modelling the effect of particle velocity and temperature during the spraying process. *Acta Mater.* **2007**, *55*, 5089–5101. [CrossRef]

13. Lima, C.; Guilemany, J. Adhesion improvements of Thermal Barrier Coatings with HVOF thermally sprayed bond coats. *Surf. Coat. Technol.* **2007**, *201*, 4694–4701. [CrossRef]

14. Pape, F.; Coors, T.; Poll, G. Studies on the Influence of Residual Stresses on the Fatigue Life of Rolling Bearings in Dependence on the Production Processes. *Front. Mech. Eng.* **2020**, *6*, 56. [CrossRef]

15. Taymaz, I. The effect of thermal barrier coatings on diesel engine performance. *Surf. Coat. Technol.* **2007**, *201*, 5249–5252. [CrossRef]

16. Loganathan, A.; Gandhi, A.S. Effect of phase transformations on the fracture toughness of t’ yttria stabilized zirconia. *Mater. Sci. Eng. A* **2012**, *556*, 927–935. [CrossRef]

17. Wellman, R.; Whitman, G.; Nicholls, J. CMAS corrosion of EB PVD TBCs: Identifying the minimum level to initiate damage. *Int. J. Refract. Met. Hard Mater.* **2010**, *28*, 124–132. [CrossRef]

18. Mercer, C.; Faulhaber, S.; Evans, A.; Darolla, R. A delamination mechanism for thermal barrier coatings subject to calcium–magnesium–alumino-silicate (CMAS) infiltration. *Acta Mater.* **2005**, *53*, 1029–1039. [CrossRef]

19. Witz, G.; Shklover, V.; Steurer, W.; Bacheogwa, S.; Bossmann, H.-P. High-temperature interaction of yttria stabilized zirconia coatings with CaO–MgO–Al2O3–SiO2 (CMAS) deposits. *Surf. Coat. Technol.* **2015**, *265*, 244–249. [CrossRef]

20. Krämer, S.; Faulhaber, S.; Chambers, M.; Clarke, D.; Levi, C.; Hutchinson, J.; Evans, A. Mechanisms of cracking and delamination within thick thermal barrier systems in aero-engines subject to calcium-magnesium-alumino-silicate (CMAS) penetration. *Mater. Sci. Eng. A* **2008**, *490*, 26–35. [CrossRef]

21. Stolzenburg, F.; Kenesei, P.; Almer, J.; Lee, K.; Johnson, M.; Faber, K. The influence of calcium–magnesium–aluminosilicate deposits on internal stresses in Yb2Si2O7 multilayer environmental barrier coatings. *Acta Mater.* **2016**, *105*, 189–198. [CrossRef]

22. Lance, M.; Thiesing, B.; Haynes, J.; Gildersleeve, E.; Sampath, S.; Pint, B. Effect of APS flash bond coatings and curvature on TBC performance on rod specimens. *Surf. Coat. Technol.* **2019**, *378*, 124940. [CrossRef]

23. Zhang, X.; Xu, B.; Wang, H.; Wu, Y. Optimum designs for multi-layered film structures based on the knowledge on residual stresses. *Appl. Surf. Sci.* **2007**, *253*, 5529–5535. [CrossRef]

24. Fuseini, M.; Zaghloul, M.M.Y. Statistical and qualitative analysis of the kinetic models using electrophoretic deposition of polyaniline. *J. Ind. Eng. Chem.* **2022**, in press. [CrossRef]

25. Fuseini, M.; Zaghloul, M.M.Y. Investigation of Electrophoretic Deposition of PANI Nano fibers as a Manufacturing Technology for corrosion protection. *Prog. Org. Coat.* **2022**, *171*, 107015. [CrossRef]

26. Fuseini, M.; Zaghloul, M.M.Y.; Elkady, M.F.; El-Shazly, A.H. Evaluation of synthesized polyaniline nanofibres as corrosion protection film coating on copper substrate by electrophoretic deposition. *J. Mater. Sci.* **2022**, *57*, 6085–6101. [CrossRef]

27. Khan, A.N.; Lu, J.; Liao, H. Effect of residual stresses on air plasma sprayed thermal barrier coatings. *Surf. Coat. Technol.* **2003**, *168*, 291–299. [CrossRef]

28. Chen, X.; Yan, J.; Karlsson, A.M. On the determination of residual stress and mechanical properties by indentation. *Mater. Sci. Eng. A* **2006**, *416*, 139–149. [CrossRef]

29. Lima, C.; Nin, J.; Guilemany, J. Evaluation of residual stresses of thermal barrier coatings with HVOF thermally sprayed bond coats using the Modified Layer Removal Method (MLRM). *Surf. Coat. Technol.* **2006**, *200*, 5963–5972. [CrossRef]

30. Ng, H.; Gan, Z. A finite element analysis technique for predicting as-sprayed residual stresses generated by the plasma spray coating process. *Finite Elements Anal. Des.* **2005**, *41*, 1235–1254. [CrossRef]

31. Zhu, J.; Chen, W.; Xie, H. Simulation of residual stresses and their effects on thermal barrier coating systems using finite element method. *Sci. China Phys. Mech. Astron.* **2015**, *58*, 1–10. [CrossRef]

32. Rajabi, M.; Aboutalebi, M.; Seyedein, S.; Ataie, S. Simulation of residual stress in thick thermal barrier coating (TTBC) during thermal shock: A response surface-finite element modeling. *Ceram. Int.* **2021**, *47*, 5299–5311. [CrossRef]

33. Abdelgawad, A.; Al-Atelh, K. Effect of TGO thickness, pores, and creep on the developed residual stresses in thermal barrier coatings under cyclic loading using SEM image-based finite element model. *Ceram. Int.* **2021**, *47*, 20064–20076. [CrossRef]

34. Ahmad, B.; Zhang, X.; Guo, H.; Fitzpatrick, M.E.; Neto, L.M.S.C.; Williams, S. Influence of Deposition Strategies on Residual Stress in Wire + Arc Additive Manufactured Titanium Ti-6Al-4V. *Metals* **2022**, *12*, 253. [CrossRef]
35. Contreras, P.Y.; Sánchez, J.D.O.B.; Salas, C.A.P.; Flores, J.M.M.; García, A.L.G.; López, I.D. Estudio de la evolución del perfil de esfuerzos residuales en recubrimientos barrera térmica depositados sobre acero inoxidable AISI 304. *DYNA* 2016, 83, 159. [CrossRef]

36. Noda, N.; Hernarski, R.B.; Tanigawa, Y. *Thermal Stress*, 2nd ed.; Taylor and Francis: Cambridge, UK, 2003; pp. 29–76.

37. Mao, W.; Zhou, Y.; Yang, L.; Yu, X. Modeling of residual stresses variation with thermal cycling in thermal barrier coatings. *Mech. Mater.* 2006, 38, 1118–1127. [CrossRef]

38. Meza, J.M.; Franco, E.E.; Farias, M.C.M.; Buiochi, F.; Souza, R.M.; Cruz, J. Medición del Módulo de Elasticidad en Materiales de Ingeniería Utilizando la Técnica de Indentación Instrumentada y de Ultra-Sonido. *Rev. Metal.* 2008, 44. Available online: http://revistademetallurgia.revistas.csic.es/index.php/revistademetallurgia/article/viewFile/95/94 (accessed on 15 May 2015).

39. Wiesner, V.L.; Bansal, N.P. Mechanical and thermal properties of calcium–magnesium aluminosilicate (CMAS) glass. *J. Eur. Ceram. Soc.* 2015, 35, 2907–2914. [CrossRef]

40. Available online: http://data.irestal.com/files/files/2012030204152933979.pdf (accessed on 20 May 2018).

41. Teixeira, V.; Andritschky, M.; Fischer, W.; Buchkremer, H.; Stöver, D. Analysis of residual stresses in thermal barrier coatings. *J. Mater. Process. Technol.* 1999, 92–93, 209–216. [CrossRef]

42. Armengol González, S. Caracterización Micro Estructural y Mecánica de Barreras Térmicas por APS y EB-PBD Degradadas por Fatiga Térmica y por Contacto. Master’s Thesis, Departamento de Ingeniería de Materiales, Universidad Politécnica de Cataluña, Barcelona, Spain, 2006. Available online: http://upcommons.upc.edu/handle/2099.1/3196 (accessed on 8 November 2016).

43. Wang, L.; Li, Z.; Ding, K.; Deng, C.; Zhang, S.; Zheng, R.; Yang, L.; Lin, X. Effects of TGO growth on the stress distribution and evolution of three-dimensional cylindrical thermal barrier coatings based on finite element simulations. *Ceram. Int.* 2022, 48, 7864–7875. [CrossRef]

44. Ahrens, M.; Vaßen, R.; Stöver, D. Stress distributions in plasma-sprayed thermal barrier coatings as a function of interface roughness and oxide scale thickness. *Surf. Coat. Technol.* 2002, 161, 26–35. [CrossRef]

45. Wu, J.; Guo, H.-B.; Gao, Y.-Z.; Gong, S.-K. Microstructure and thermo-physical properties of yttria stabilized zirconia coatings with CMAS deposits. *J. Eur. Ceram. Soc.* 2011, 31, 1881–1888. [CrossRef]