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Static-Structural Analysis of Gas Turbine Blade Fabricated with Titanium Based MAX Phase Materials

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Abstract—Gas turbines are widely used in the aviation, marine, and energy industries. Gas Turbine engine parts are generally made of Ni-based superalloys, but their service temperatures are limited. Max phase materials is a candidate material for turbine blades. Therefore, if the turbine blade is produced from the MAX phase, various analyzes have been made with the Aysys 2020 R2 program to obtain information about the static and structural properties of this produced material. In Ansys program; boundary conditions were determined such that rotational velocity (in the X axis) was 1000 rad/s, thermal condition was 1000 ºC, and pressure was 1 MPa. Total deformation, equivalent stress, and equivalent elastic strain datas of max phase materials (such as Ti_2AlC, Ti_3AlC_2, Ti_4AlN_3, and Ti_3SiC_2) analyzed with Ansys were compared with the actual data of the commercial product CMSX4. The material with the least total deformation was Ti_3SiC_2 (5.94 µm) which was 8 times less deformed than CMSX4 (49.58 µm). The material with the least equivalent stress value was Ti_2AlC with 9.97 MPa. The material with the highest ductility was CMSX4, with an elastic stress value of $2.56e^{-4}$ µm/µm, while the material with the closest ductility was Ti_4AlN_3 with a value of $3.91e^{-5}$ µm/µm. In other words, CMSX4 is 1.78 times more ductile than Ti_4AlN_3. As a result, according to the study, it was seen that max phase materials are more brittle than CMSX4, although it is actually candidate materials for turbine blades due to lower density, high temperature stability.

Index Terms—Gas turbine blade, Numeric analysis, MAX phase

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1 INTRODUCTION

Gas turbine engines operate on the principle of converting the heat energy generated by the combustion of fuel into kinetic energy. The compressor is activated with the air sucked into the engine from the front turbines. However, the energy obtained with this air is not sufficient. For this reason, fuel is mixed into the air accelerated by the compressor in the combustion chamber. Thus, more energy is obtained. This energy provides thrust for the movement of air and sea vessels. Gas turbine engines are also used in power plants to generate energy. The turbine temperature is around 1000 ˚C in the combustion chamber area. There are many turbine blades in this area. These blades are made of single crystal super alloys. These materials are preferred due to their high creep resistance. In addition, combustion chamber parts are coated with ceramics with low thermal conductivity. These coatings are called thermal barrier coatings. Thermal barrier coatings protect turbine blades from aggressive environment effects. It allows them to be used for a longer life.

In parallel with technological developments, many studies are carried out to make gas turbine engines more efficient. In these studies, instead of the traditional materials used today, lower density and higher temperature resistant materials are being explored. This is because the use of lower density materials lightens the engine. Thus, higher powers can be achieved with less fuel consumption. Thus, engines with low emissions can be produced. In addition, the use of higher temperature resistant materials allows more fuel to be fed into the combustion chamber. Thus, more powerful engines can be produced. This greatly increases the speed of aircraft. For this purpose, some engine components have started to be produced from SiC/SiC CMCs. However, under aggressive turbine operating conditions, oxidation of SiC causes corrosion problems. To solve these problems, researchers have produced coatings called environmental barrier coatings on SiC CMCs. Thus, the performance of SiC CMCs has been slightly improved. But there is still a need for alternative materials.

MAX phase materials are likely to be used in gas turbine engines due to their low density, high temperature oxidation resistance, good creep resistance, good thermal shock resistance, and phase stability at high temperatures. MAX phase materials are generally formulated as Mn+1AXn (n= 1- 5), where M stands for transition metals, A stands for group A elements and X stands for Carbon (C) or Nitrogen (N). They have a uniqe microstructural feature with nano layers. There are systems with elements such as Ti, V, Ta, Nb in the letter M. Among these systems, Ti based MAX phases are the most subject to scientific studies. MAX phase alloys with the highest elastic moduli are: Ti_3SiC_2 and TiAlCN, Ti_4AlC_3. The fracture toughness of Ti_3SiC_2 is the highest among the MAX phase alloys. The most important feature of MAX phases in general is their phase stability. According to the literature, Ti_3SiC_2 has excellent oxidation resistance up to 700 °C [2] and phase stability up to 2300 ˚C [1], and the melting temperature for Ti_3SiC_2 is above 3000 ˚C [1]. The phase stability of Ti_3SiC_2, Ti_3AlC_2, Ti_2AlN compositions from MAX phases are shown in Fig. 1.

Ti_3SiC_2, Ti_3AlC_2, Ti_2AlN compositions can maintain their

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phase stability up to 1300 °C. Ti_3SiC_2 alloy behaves more stable than the others and when it loses its stability, it forms the TiC phase, which is thermodynamically more stable. Ti_3AlC_2 ternary composition undergoes a sudden phase change after 1300˚C and forms TiC phases together with Ti_2AlC, a second MAX phase.

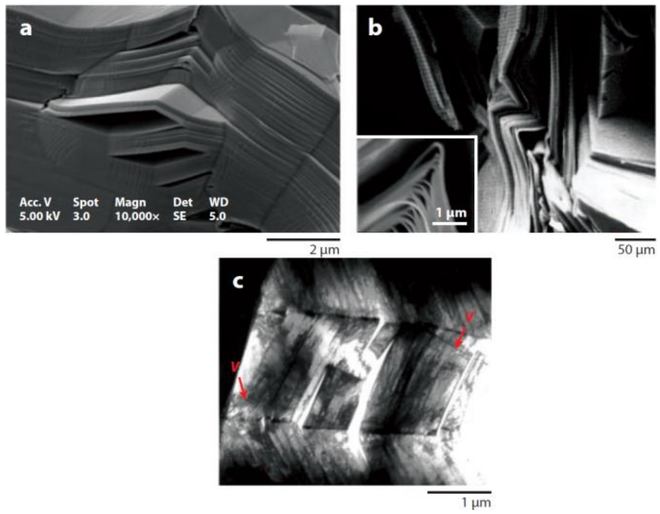

Fig. 1. Typical examples of Max Phases at different length scales [2].

2 Methodology

The Density (g/cm^{-3}), Young's modulus(GPa), and Poisson's Ratio properties of Ti based alternative materials (Ti_3SiC_2, Ti_3AlC_2, Ti_2AlN) and CMSX4, which is currently used as a commercial product, are given in Table 1.

TABLE 1
MECHANICAL PROPERTIES OF MATERIALS

Materials	Density (g/cm^{-3})	Young's modulus(GPa)	Poisson's Ratio
CMSX4	8.927	84	0.39
Ti_2AlC	4.1	277	0.19
Ti_3AlC_2	4.2	297	0.20
Ti_4AlN_3	4.7	310	0.22
Ti_3SiC_2	4.52	343	0.20

Turbine blade part was designed in Ansys 2020 R2 program. By creating elements in the Turbine Blade part designed in the program, exactly 147458 elements were created. The width and length of each element is 1mm. Fig. 2 shows the turbine blade designed with Ansys and divided into elements.

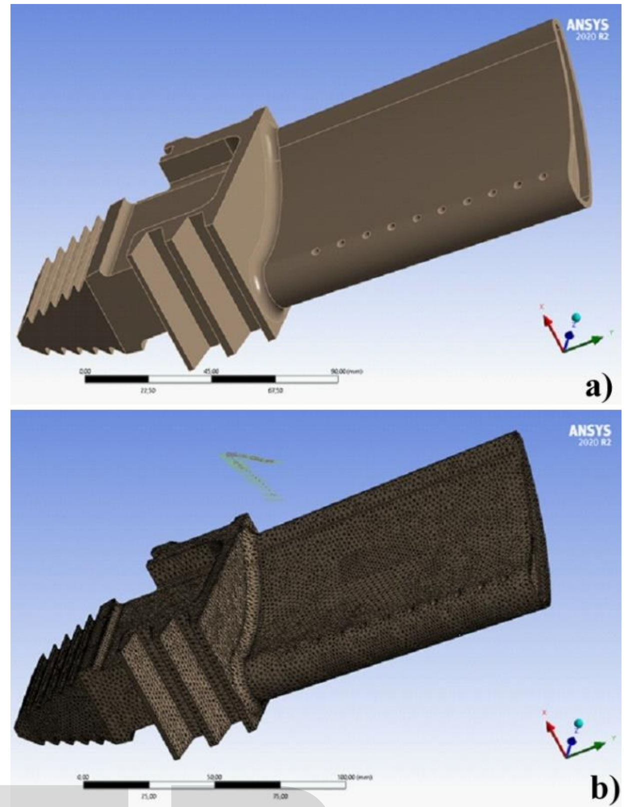

Fig. 2. (a) CAD Model and (b) Mesh Model of Turbine Blade.

The operating conditions of the turbine blades in the hot zones of the aircraft engine are investigated. In the light of these data, in Ansys program; boundary conditions were determined such that rotational velocity (in the X axis) was 1000 rad/s, thermal condition was 1000 ºC, and pressure was 1 MPa. Total deformation, equivalent stress, and equivalent elastic strain datas of max phase materials (such as Ti_2AlC, Ti_3AlC_2, Ti_4AlN_3, and Ti_3SiC_2) analyzed with Ansys were compared with the actual data of the commercial product CMSX4. The created experimental environment is shown in Fig. 3.

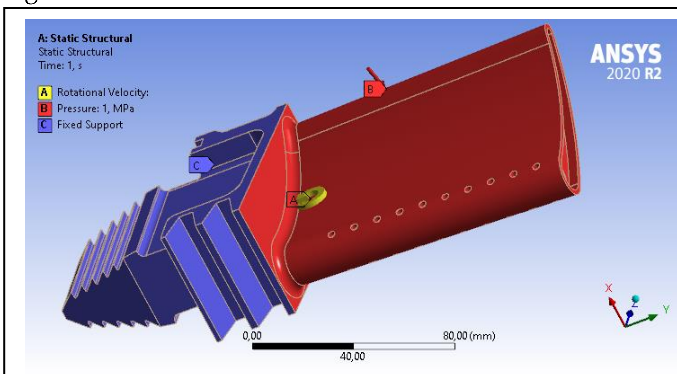

Fig. 3. Boundary Conditions of Analysis

3 Results & Discussion

The results of the Ansys 2020 R2 structural analysis are as shown in Table 2.

TABLE 2
STRUCTURAL ANALYSIS RESULTS

		CMSX4	Ti_2AlC	Ti_3AlC_2	Ti_4AlN_3	Ti_3SiC_2
Total Deformation (µm)	Max	302.29	40.598	38.919	43.815	36.28
	Average	49.583	6.6446	6.3691	7.1711	5.9378
Equivalent Stresses (MPa)	Max	216.59	97.387	99.871	112.13	107.49
	Average	21.037	9.9688	10.198	11.379	10.975
Equivalent Elastic Strain (µm/µm)	Max	2.59e-003	3.53e-004	3.38e-004	3.7929e-004	3.1488e-004
	Average	2.56e-004	3.67e-005	3.50e-005	3.9065e-005	3.2625e-005

As can be seen in Fig 4 and Table 2, Ti_3SiC_2 material was the experimental group with the least total deformation.

The total deformations reached a maximum in the same places for all the materials used in the experiment, in the corner region at the top of the turbine blade, which is indicated in figure 4 by maximum in red. If the total deformation is less in Ti_3SiC_2, it means that the material stretches less. This behavior is actually a property that should be present in the turbine blade.

Structures such as steel often undergo plastic deformation and subsequent fracture. For a safe design, it is necessary to design structures so that they are always within the elastic limit, i.e. without plastic deformation. Since most of the experiments are performed under simple loading conditions (such as uniaxial stress), it is often a problem how this can be related to the general loading conditions actually observed. Equivalet Stress (Von Mises stress) is a value calculated to determine whether the structure has undergone plastic deformation under any loading condition. The calculated stresses at any point can be written as a scalar value, known as the Von Mises stress, which can be compared with the experimentally measured yield point.

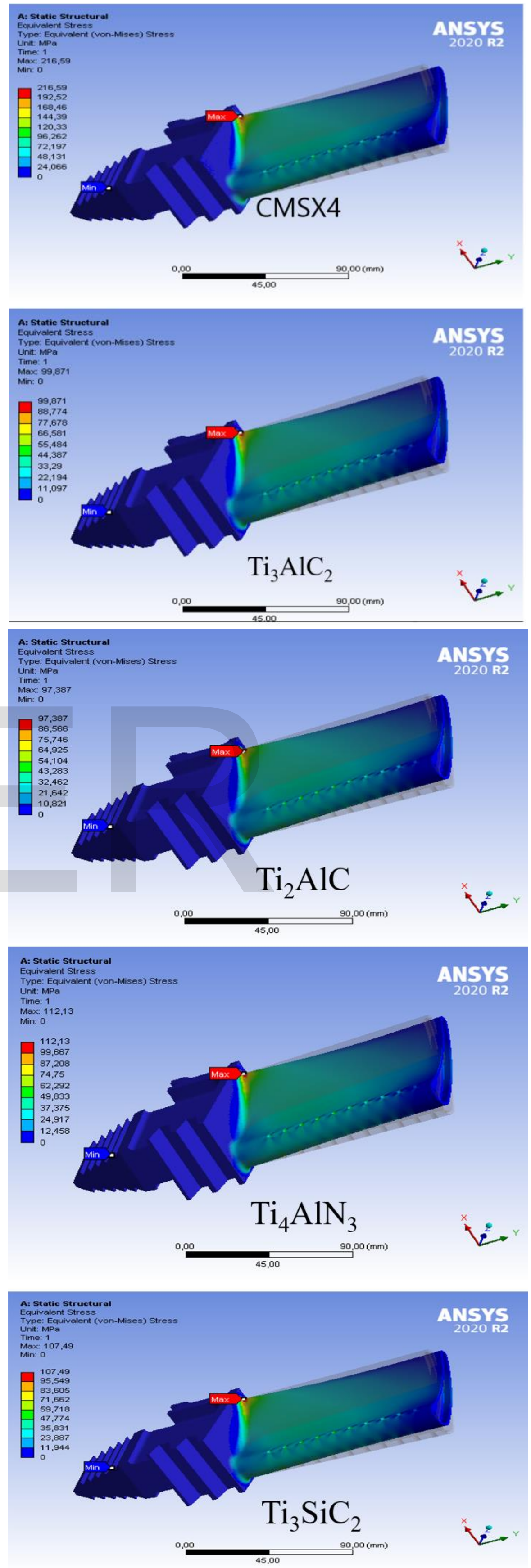

Fig. 4. Total deformation results of materials.

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As can be seen in Figure 5, Ti_4AlN_3 is the material with a stress value closest to CMSX.

The equivalent elastic strain is defined as the limit for the values of strain up to which the object will rebound and come back to the original shape upon the removal of the load. Elastic limit is defined as the point on the stress-strain curve where the object changes its elastic behavior to plastic behavior.

Materials with high elastic strain also have good ductility. For this reason, after the commercial CMSX4, the material with the equivalent elastic strain value closest to it is Ti_4AlN_3 as shown in Figure 6. In addition, as seen in Figure 6, while strain occurred on the entire surface in CMSX4, strain occurred only in the region called root zone in max phase materials.

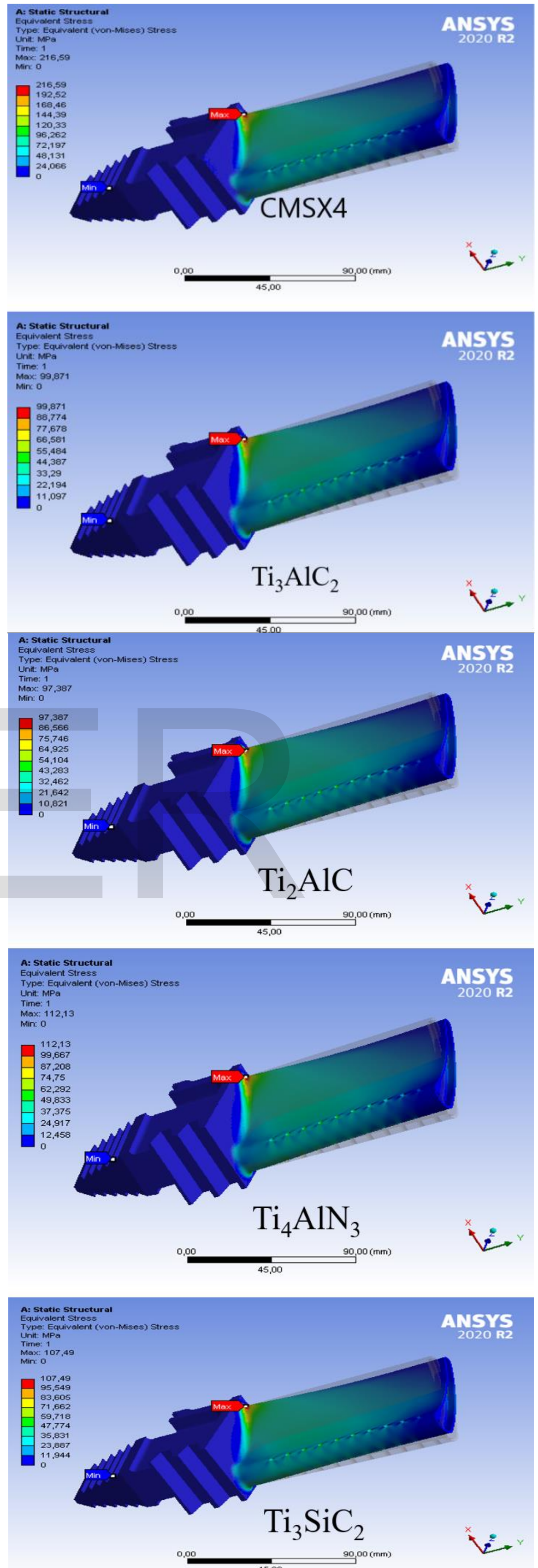

Fig. 5. Equivalent Stress results of materials.

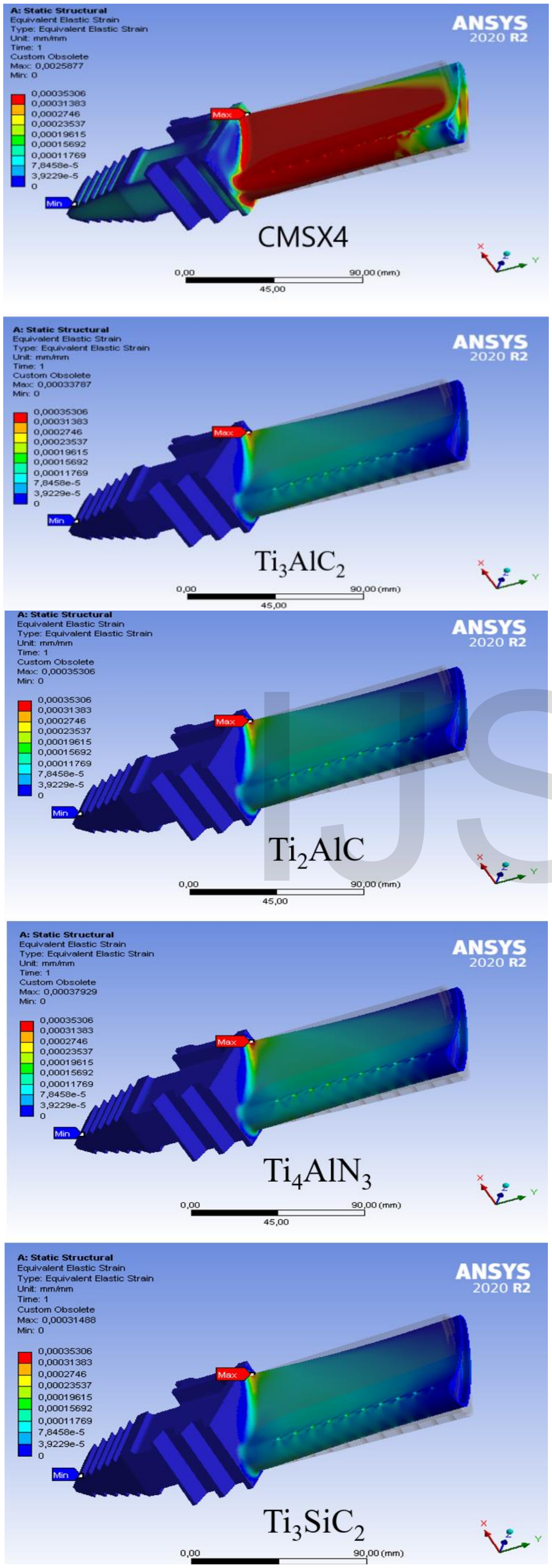

Fig. 6. Equivalent Elastic Strain results of materials.

4 Conclusion

The material with the least total deformation was Ti_3SiC_2 (5.94 µm) which was 8 times less deformed than CMSX4 (49.58 µm). The material with the least equivalent stress value was Ti_2AlC with 9.97 MPa. The material with the highest ductility was CMSX4, with an elastic stress value of $2.56e^{-4}$ µm/µm, while the material with the closest ductility was Ti_4AlN_3 with a value of $3.91e^{-5}$ µm/µm. In other words, CMSX4 is 1.78 times more ductile than Ti_4AlN_3. As a result, according to the study, it was seen that max phase materials are more brittle than CMSX4, although it is actually a suitable material for turbine blades because it has high temperature resistance and very low density.

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