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RESEARCH

Airworthiness Certification of Fe-Si_3N_4-graphite Brake Composites for Military Aircraft

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ABSTRACT

Metal matrix hybrid composites are usually preferred for high energy aircraft (1-10 MJ) brake pads (HEABP) applications. The report focuses mainly on the evaluation of the wear and braking performance of the composite for the military aircraft applications. In this paper, the design and processing of a typical HEABP composite have been discussed in detail. The airworthiness qualification tests for the HEABP and the brake units are outlined with details. Also, brake testing parameters calculations derived from the typical aircraft data are presented for both the laboratory and full scale dynamometer tests. A case study of Fe-Si_3N_4- graphite composite pads is presented to exemplify the steps involved in the design, development, and airworthiness certification of HEABPs for the 8 MJ energy military aircraft. From the microstructure and wear surface morphology analysis and the results of brake performance parameters, functional tests and aircraft trials, it is concluded that the Fe-Si_3N_4- graphite composite has a minimum life of 200 normal energy landings with excellent braking performances.

1. INTRODUCTION

A typical high energy aircraft brake pad (HEABP) unit consists of alternate stator and rotor multi brake discs, called as a heat pack [1]. The brake pads are usually assembled with stator discs. The rotor discs are typically grey cast iron or low alloy (Cr-Ni) steel. The hardness of the rotor is selected to be two times the stator brakepad so that brakepads wear out preferably. At one end of the brake unit, the brake cylinder housing is attached with the pressure plate. The other side of the pressure plate is fitted with brake pads. The other end of the brake unit has a torque tube in which the inner side that is in contact with the rotor disc is fitted with brakepads. The outer side is attached to the hydraulic actuator. Stator brakepads and rotor discs are alternatively placed in between the pressure plate and the torque plate. The main function of brake pads is to convert the kinetic energy of moving aircraft to the thermal energy by providing the necessary friction during the braking process [2]. The HEABP is usually designed to stop the aircraft within a short time span of 10 - 30 s depending on the weights (5000-27000 kg) and brake application speeds (180-300 km/h) of the aircraft. It implies that the aircraft stops with in a distance of 300-1500 m with a maximum deceleration of 0.3 g. No single pad composition would be able to satisfy the diverse braking requirements. Therefore, HEABPs are tailor-made to the specific aircraft requirements such as kinetic energy, stop time, stop distance, dynamic and static co-efficient of friction, temperature rise, and wear loss [2-7].

The HEABP composites are a complex multi-constituents system processed through powder metallurgy for the specific aircraft requirements as described above. The typical brake composites consists of following important constituents: (1) metal or alloy (Fe, Cu, Brass, steel) as a matrix to provide strength, stiffness, specific heat and thermal conductivity properties, (2) particle reinforcements (SiC, Si_3N_4, SiO_2, mullite, Al_2O_3) to support the brake load, and to provide the necessary friction and wear resistance properties, (3) solid lubricants (graphite, MoS_2, h-BN, PbS, Sb_2S_3) to stabilize the friction and to provide the brake sequel and seizure resistance properties, (4) fillers (glass, aramid fibers), frictional additives ($BaSO_4$, $CaSO_4$) , and ceramic particle wetting agents to provide various properties such as manufacturability, bonding strength, weight reduction, durability, mechanical integrity, brake noise reduction, friction and wear properties adjustment, thermal resilience, hardness, fracture toughness [2,7-9]. The proportion of each ingredient is judiciously selected to optimize the diverse properties requirements.

In the past, development studies on various HEABP composites such as Cu/SiC/graphite, Cu/silica/graphite/MoS_2, Cu/mullite/ MoS_2, Fe/SiC/graphite and so on were carried out for the Indian defence programs. The numerous combinations of compositions were derived for military aircrafts of 3-19 MJ.

The ceramic reinforcement of Si_3N_4 has many advantages: (1) high thermal stability and melting point, (2) high fracture toughness, (3) excellent wear resistance, (4) excellent chemical and thermal shock resistance, (5) very low thermal expansion coefficient upto 1900 ^oC [10,11]. Another advantage of Si_3N_4 is that it reacts with the air and forms the silicon oxide (SiO_2) layer which stabilizes the friction coefficient and reduce the wear rate of the composite at elevated temperatures. Also, this layer serves as a protection against the oxidation of composite. These particles were not tried out in the HEABP yet, atleast in India.

In light of the above facts, we have designed a HEABP composition including Si_3N_4 as a ceramic reinforcement for 8 MJ military aircraft. To the best of our knowledge, there is no open literature in the airworthiness certification of brakepads. Also, the design and qualification testing requirements of the HEABP are nowhere found available in the literature. To address the above needs, we have taken up this work. In this work, the first section describes the material selections and processing of the HEABPs. Qualification tests required for airworthiness certification are described subsequently. Later, results of a typical Fe/Si_3N_4/graphite HEABP composite are presented and discussed in brief. Based on the discussion, the conclusions are presented in the last section.

2. PROCESSING

2.1 Selection of Material Composition

The raw materials are selected based on the number of design experiments carried out on various combinations of compositions (Fe, silica/B_4C/SiC/Si_3N_4/mullite/Al_2O_3,graphite/MoS_2) to meet the brake design requirements of various parameters i.e. brake torque , stop time , stop distance , static and dynamic coefficient of friction , temperature rise etc. From the results of these experiments, each raw material type and specification are fixed and optimized.

Many development studies were carried out to relate the MMC hybrid (Metal-Ceramic particles - Solid lubricants) composites to the aircraft energy, as listed in Table 1. For 8 MJ braking energy conditions of the military aircraft brake, it was found that Fe-Si_3N_4-graphite with small amounts of Cu, Sn, and asbestos composite was suitable to meet the brake design requirements. The exact composition of the composite is highly confidential due to the sensitivity of the defence projects. After finalization of the composite composition, the design agency prepares the prototype manufacturing procedure and the test schedules in co-ordination with airworthiness agency to qualify the component airworthiness.

Table 1. Various composites developed for different aircraft kinetic energies.

Composition	Aircraft kinetic energy
Cu-silica-graphite	5.3 MJ
Cu-mullite- graphite	5.6 MJ
Cu-mullite-MoS_2	7 MJ
Fe-Si_3N_4- graphite	8 MJ
Fe-Si- graphite	13 MJ
Fe-SiC- graphite	19 MJ

2.2 Typical Prototype Manufacturing Steps

Mixing of the Powders: The sequence of mixing is very important to get good quality of the powder mix. We found that the following procedure is appropriate in providing the homogenous mix: the metal powders (iron + copper + tin) are first mixed in a double cone blender for about 12-16 h, called as Mix A. Then, the ceramic particles (silicon nitride, asbestos) are added to the Mix A and mixed for 2 h, called as Mix B. Finally, the other constituents namely, solid lubricants, friction additives are added to the Mix B to form a final mixture of powders. This practice is adopted in all our HEABP composite fabrications. We understand that the sequence of mixing of powders based on its nature such as metal, non metal, and properties such as hardness, lubricity is important in order to yield a highly homogenous mix.

Powder Compaction: The mixed powders are compacted under the hydraulic pressure in a single die uniaxial press. The die has a configuration of brake pad shape. The compaction pressure varies mainly with the shape and area of the product, the die wall and the green compact friction, and the powder constituent's type and amount. The typical compaction pressure for Fe based HEABP composites is about 30-60 MPa. We usually prefer to design an oval shape brake pad sector so that they can be easily riveted with stator plates.

Pressure Sintering of Brake Pads: The steel back plate is electroplated with nickel of few microns (70-120 μm) thickness. Ni plated steel plate is diffusion treated at 800 °C under reducing H2 atmosphere to form the uniform layer of Ni on the steel plate and to improve the bonding with the steel plate. The back plate is intended to provide load support during impact loading conditions encountering in the braking operations, and to facilitate riveting with the stator plate. The green compact placed over the diffusion treated back plate, called brakepad, is stacked one above another, as shown in Fig. 1. The brakepad stacks are placed in a circle with 120° apart. The dead weight is placed above the stacks to apply the sintering load. The sintering load is applied hydraulically. The thermal and mechanical bonding of constituents of the brake pads and, the back plate and the brake pad are established by the temperature and pressure (pressure sintering). Fe-Si3N4-graphite composites are pressure sintered at a temperature and pressure of 10000 C and 3-5 MPa respectively in a bell furnace for 3 h under reducing H2 atmosphere. The advantages of pressure sintering are that (1) it provides high uniform densification or consolidation close to hot isostatic pressing, (2) the capital and operating cost of the equipments are less, and (3) it is an ideal set up for batch operations. Figure 1 illustrates the stacking of brake pads in the pressure sintering operation.

Fig. 1. Pressure sintering unit showing the alternate stacking of the back plate and green compact.

2.3 Airworthiness Qualification Testing

To qualify the flight worthy of the composite brake pads and the brake unit, qualification tests are configured in three phases: first phase involves the qualification of composite materials in the laboratory scale, the second phase covers the qualification of the brake unit in the functional level, and the third phase involves real aircraft trials for various extreme flight envelope conditions [12].

Phase I - Composite Material Qualification Testing

The following material tests are carried out to qualify the brake pads for fitment in the brake unit for functional level testing.

- Powder characterization (purity, particle size distribution, impurities content, apparent density (ASTM B212-48 [13]), tap density, compressibility).
- Chemical composition analysis by wet analysis according to the in-house standards.
- Brinell hardness test according to the ASTM E 10 standard [14].
- Microstructure characterization according to the ASTM E407 standard [15].
- Complete dimension inspection according to the component drawing.
- Bend test according to the BS 1639 [16].
- Laboratory scale reduced energy level 2-pad configuration dynamometer test according to the in-house standards.

Phase II – Brake Unit Full Qualification Testing

- Brake performance evaluation (Normal energy and Rejected take-off energy level) by full scale dynamometer test according to the MIL –W-5013L standard [17]
- Static torque test.
- Brake fusing level stop test.
- Brake taxi and parking test.

Phase III – Aircraft trials

- Ground tests (Taxi trials).
- Flight landing tests covering spectrum of extreme cases landing according to the aircraft manuals.
- Service lifing trials.

In the following section, we describe the results of Fe/Si_3N_4/graphite composites for 8MJ military aircrafts, and discussed in brief with regard to the airworthiness qualification testing.

3. RESULTS AND DISCUSSION

3.1 Composite Material Qualification Testing

Bend Test: This test is carried out according to the BS1639-1964 standard [16]. The objective of this test is to ensure the interfacial bond between the back plate and the composite. The brake pad is placed in a three point bend set up and loaded until cracking. If the failure exposes the back plate and the composite, then the bonding is poor and the part is rejected.

Aardness Test (Brinell): Harness test is carried out according to the ASTM E10 [14]. We use the load of 10 kg and 1 mm steel ball indenter for testing. The objective of this test is to ensure that the composite has less variability in the hardness, and the hardness value is substantially lower than the rotor disc so that the brake pad wears out preferably. Fe/Si_3N_4/graphite composites have the hardness values between 75-100 BHN. The variation in the hardness values is mainly from the wide hardness variation in the composite constituents.

Chemical Analysis: The objective of the chemical analysis is to confirm the chemistry of the brake pad to avoid any inadvertent errors during mixing. The scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) is also sometimes employed to verify the composition.

Microstructure Analysis: Microstructure is analyzed in the optical microscopy and SEM/EDS. The sample preparation and testing procedure are laid down in the ASTM E 407 standard [15]. The phase identification of the composite and the back plate, the bonding between the composite and the back plate is analyzed. Also, the SEM/EDS analysis is carried out to identify the reaction between the constituents, to examine the back plate and the composite interlayer bonding characteristics, and to study the matrix and particle interface structure analysis. The microstructures of the Fe/Si_3N_4/graphite composite and the back plate are shown in Figs. 2 and 3. The microstructure of the composite has homogenous distribution of graphite, Si_3N_4, and other fillers and frictional additives in the iron matrix. Matrix constituents predominantly the pearlite structure. The pearlite may be formed by the diffusion of carbon from graphite to the iron matrix. It was found from the SEM study that the reaction between the tin and the copper formed the Cu-Sn compounds to facilitate the liquid phase sintering. There were some oxide particles and FeS particles present in the matrix. The sulphur from one of the friction additives reacted with the matrix and formed FeS particles. The back plate has the pearlite dispersion in the ferrite matrix confirming the low carbon steel. The interface between the composite and the back plate is intact without any delamination cracks. Also, Ni plated layer is clearly delineated in the microstructure. The layer thickness is determined to be 70-100 μm.

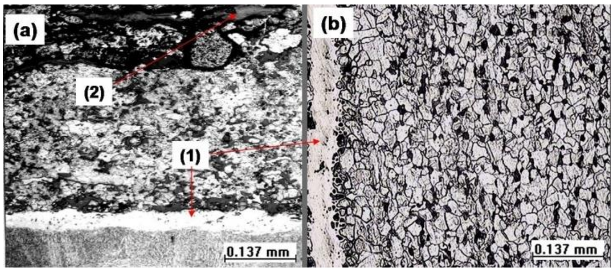

Fig. 2. Optical micro images of the (a) brake pad composite, (b) back steel plate showing interdispersion of pearlite in the ferrite matrix. (1) Ni plated layer (70-100 μm thick) bonds the composite with back plate, the interface is seen to be continuous and free from any defects. (2) Graphite particles.

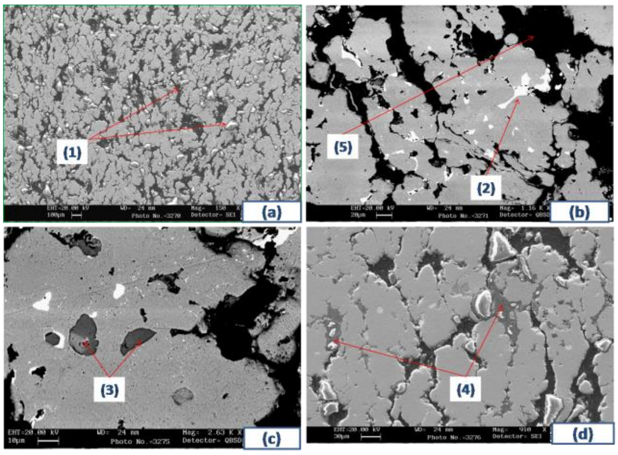

Fig. 3. SEM micro images of the brake pad composite. (1) Uniform dispersion of Si_3N_4 particles in the iron matrix, (2) Cu-Sn compounds, (3) Iron sulphide particles, (4) Oxide particles, (5) Graphite lubricant.

Lab Scale Dynamometer Test: A laboratory scale dynamometer test is the quick and cost effective method to screen the wear and braking performance of the brake pad composites. It saves time and money in identifying the right composition and processing parameters for particular braking energy applications. In the laboratory test, only two brake pads are tested. The sample preparation, testing procedure, properties, microstructure details of the counter surface material, dynamometer layout, and the operation are described elsewhere [18-19]. The input testing parameters (rotational speed and brake force) are derived from the full scale dynamometer input parameters. The calculation steps are given below:

$$\mathbf{E} = \frac{1}{2} * \mathbf{M} * \mathbf{V}^2 \tag{1}$$

$$\mathbf{E_2} = 2 * \frac{\mathbf{E}}{\mathbf{x*y}} \tag{2}$$

$$\mathbf{E_2} = 0.5 * \mathbf{I} * \boldsymbol{\omega}^2 \tag{3}$$

$$\boldsymbol{\omega} = 2 * \boldsymbol{\pi} * \mathbf{N}/60 \tag{4}$$

Eq (2) is equated to the rotational kinetic energy of the dynamometer to find the rotational speed.

Where E is the kinetic energy of the aircraft (J), M is the mass (N), V is the speed (m/s), E_2 is the kinetic energy absorbed by the 2 pads (J), x is the total number of brake pads in the brake unit, y is the number of braking unit per aircraft, I (Nms^2) is the mass moment of inertia of the flywheel, ω (rad/s) is the rotational speed, and N (rpm) is the number of revolutions per minute

Putting Eq (4) into Eq (3) and rearranging the terms gives the N value. The brake force for the laboratory scale test is derived from the following relations.

Brake $force_2$ = (Aircraft brake pressure * Total brake piston area of brake unit)/Number of brake pads per face of brake disc.

The output braking performance parameters are stopping distance (SD), stopping time (ST), mean and peak torque (T_m, T_p), coefficient of friction (CoF), mean and peak drag, brake temperature rise, and wear loss (by thickness and by mass). The CoF and SD are derived quantity from mean torque and stopping time respectively. The CoF is related to T_m by the following relation.

$$\boldsymbol{CoF} = \boldsymbol{T_m}/(\boldsymbol{F} * \boldsymbol{R}) \tag{5}$$

Where F is the brake force of the lab scale test, R is the radial distance from the centroid of the disc to the pad. The SD is derived from the ST using the Newton law of motion.

Table 2. Brake input Parameters for 8 MJ energy military aircraft in a lab scale dynamometer test.

Kinetic energy of two brake pads to be simulated in a lab scale dynamometer test [kJ]	1119
Inertia of fly Wheel [Nm^2]	30.9
Speed of fly wheel [rpm]	840
Brake Force [N]	2403

Typical brake input parameters of the 8 MJ energy military aircraft having 2 braking units and 48 pads per unit are given in Table 2.

The brake performance parameters should be expected to meet in the following ranges for the above testing conditions to qualify for the full scale dynamometer test, and it was found that the Fe/Si_3N_4/graphite composite meets the requirements:

(a) Stopping time or distance (max) – 3-8 s or 31-70 m.

(b) Mean dynamic CoF – 0.25-0.35.

(c) Brake temperature rise (max) – 150 ^{o}C.

(d) Wear loss (brakepad composite) (max) for 50 braking stops – 20 g (mass), 0.5 mm (thickness).

3.2 Brake Unit Full Qualification Testing

Full Scale Brake Dynamometer Test: After the qualification of the brakepads for the lab scale dynamometer tests and other material tests, the brake pads are assembled into the brake unit for full scale dynamometer test according to the Mil W-5013K standard. Before beginning the test, pads are given bedding-in operation to prepare the surface for the test. The bedding-in operation forms the tribofilm which stabilizes the friction and wear rate during normal energy braking stops. The bedding-in procedure is given elsewhere [18-19]. The brake unit in the full scale dynamometer test is shown in Fig. 4.

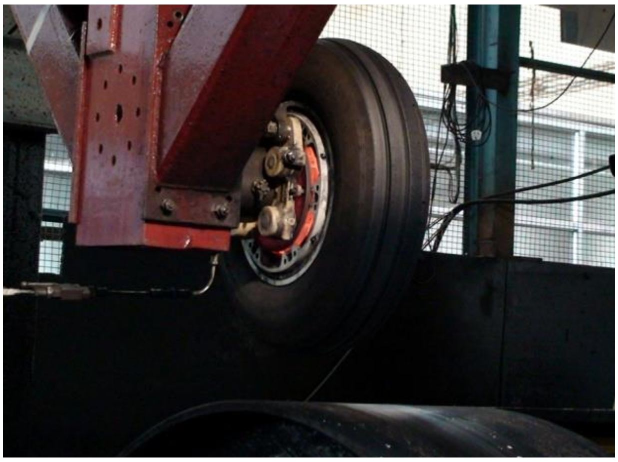

Fig. 4. Brake unit assembly in the full scale Dynamometer.

The full scale test has usually 50 normal energy (N.E) braking stops followed by 1 rejected take-off energy (RTO.E) condition braking stop. The input parameters for the test are derived from the flight manual. Typical input parameters of the full scale dynamometer test for the 8 MJ energy military aircraft are given in Table 3.

Table 3. Brake input Parameters for 8 MJ energy military aircraft in a full scale test.

Test input parameters	Conditions Simulated for test under	
	Design landing (Normal)	R.T.O
Brake Energy	7.76 MJ	8 MJ
Gyrating mass inertia	44145 Nmsec^2	44145 Nmsec^2
Gyrating mass rotation	400 rpm	640 rpm
Brake pressure	6.977 MPa	9.756 MPa
Radial load on the wheel	27.56 kN	42.5 kN

The brake performance parameters should be expected to meet in the following ranges for the above testing conditions to qualify for the aircraft trials, and it was found that the Fe/Si_3N_4/graphite composite meets the requirements.

(a) Stopping time or distance (max) – 22-34 s (N.E), 42 s (RTO.E) or 583-883 m (N.E), 1280 m (RTO.E)

(b) Mean dynamic CoF – 0.2-0.25 (N.E), 0.16 (RTO.E)

(c) Brake temperature rise (max) – 523 ^{o}C (N.E), 995 ^{o}C (RTO.E)

(d) Wear loss (rotor) (max) – 200 g (mass), 1.2 mm (thickness) for N.E condition

(e) Wear loss (brakepad composite) (max) – 410 g (mass), 3 mm (thickness) for N.E condition.

The photograph of the brake pad composite assembly (stator) and rotor segments after bedding-in and completion of 50 normal energy braking stops and 1 RTO stop are shown in Figs. 5-6. As can be seen in Figs. 5(a) and 6(a), the bedding-in operation provides the uniform tribofilm to stabilize the friction and wear rate. Fig. 5(b) shows many features such as chipped-off regions, edge cracks, abrasive grooves, and ploughed regions with extensive oxide scales after 50 N.E+1RTO braking stops. The high temperature rise in the order of 995 ^{o}C causes the composite to lose its strength and thermal stability properties resulting huge wear loss with high brake fade characteristics after the RTO brake stop. The rotor steel sectors show oxide scales without any surface cracks even after the RTO test, as seen in Fig. 6(b).

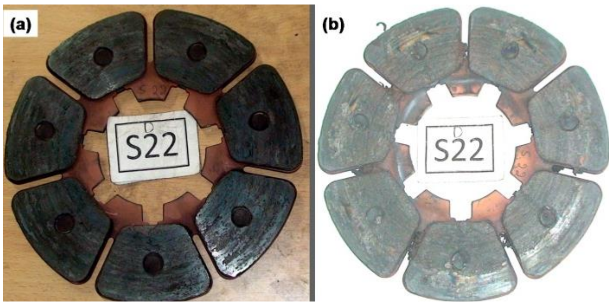

Fig. 5. Brake stator showing the assembly of brake pad sectors (a) Pad condition after bedding-in operation before the full scale dynamometer test, Pad shows the uniform tribofilm at the surface, (b) Pad condition after 50 normal energy braking stops and one rejected take off stop, Pad shows the chipped-off regions, edge cracks, abrasive grooves, and ploughed regions with extensive oxide scales.

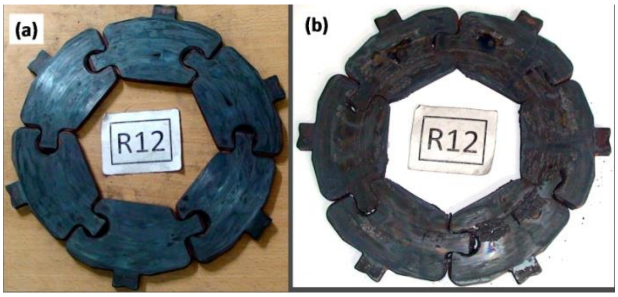

Fig. 6. Brake rotor showing the assembly of steel segments (a) Pad condition after bedding-in operation before full scale dynamometer test, Pad shows the uniform tribofilm at the surface, (b) Pad condition after 50 normal energy braking stops and rejected take off stops, Pad shows the ploughed regions with extensive oxide scales.

Static Torque Test: In this test, the capacity of the brake to hold the aircraft while the engine is started to run is checked. The aircraft mass is simulated as a wheel load during the test, the brake operating pressure and tyre pressure are set to the standard value. One part of the steel plate or belt is inserted between the tyre and the fly wheel of the dynamometer. The other end of the plate or belt is connected to the hydraulic actuator loading system. The load is progressively increased to pull the plate or belt till the tyre slips. The load at which the tyre slip is recorded as the static load to calculate the static torque value. In the present example of the Fe/Si_3N_4/graphite composite qualification, the tyre pressure was set to 1.275 MPa, the brake operating pressure was set to 10 MPa, the wheel load was set to 28 kN, and the static torque and static CoF value were found to be in the range of 3100-3600 Nm and 0.31-0.35 respectively.

Brake Fusing Level Stop Test: In this test, the wheel is unloaded after 25 normal energy braking stops in the full scale dynamometer test. The parking brake pressure is applied to the brake unit and the wheel is freely rotated by hand to check for any brake fuse or wheel lock. If the wheel freely rotates, then there is no wheel lock or brake fuse in the brake unit system. In the present example of the Fe/Si_3N_4/graphite composite qualification, the parking brake pressure of 10 MPa was applied during the test. We found that there is no wheel lock or brake fuse in the brake unit

Brake Taxi and Parking Test: This test is also similar to the brake fusing level stop test. In this test, the loaded wheel after completion of 35 normal energy braking stops in the full scale dynamometer test is rolled against the drum for 3 km distance and then the wheel is unloaded. The brake pressure is changed to the parking brake pressure and maintained for 1 h. After 1h, the pressure is released and the free rotation of the wheel and the brake fuse or wheel lock is checked. If there is no brake fuse or wheel lock, then the brake unit is passed the test. In the present example of the Fe/Si_3N_4/graphite composite qualification, the brake unit has passed the test.

3.3 Aircraft Trials Testing

Ground and Flight Trials: The aircraft trials are carried out using the actual aircraft as a test bed after successful completion of the full scale dynamometer tests. The test aircraft is fitted with test brakes which are assembled with the prototype brake pads. These trials are carried out with varied aircraft mass and landing speeds to cover the entire spectrum of aircraft energy. The brake performance parameters such as stop time, brake torque, temperature rise, stop distance and others are recorded and compared with the results of the full scale dynamometer test.

The present example of Fe/Si_3N_4/graphite composite brake pads was successfully tested at the various braking speed (60-220 kmph) and maximum aircraft weight (6000-9000 kg) and found satisfactory brake feel to the pilot with acceptable wear loss after 10 landings.

Service Lifing Trials Test: After successful completion of the aircraft trials, the brake pads will undergo the field evaluation trials to assess the lifing of the brake pads. The braking performance and wear loss are evaluated every 10 braking stops upto 50 stops, and then the data are extrapolated to determine the life and performance efficiency, overhaul period of the brake pads and brake units. The present example, Fe/Si_3N_4/graphite composite brake pad has the life of 200 normal energy landings before overhaul.

3.4 Airworthiness Certification

Airworthiness agencies involve in the every phase of testing after finalizing the process design. Certificate of the part is required in each phase to move to the next phase. Certification is granted after verification of the process and test report conformance with the process design, drawing and test schedule documents. After the full scale dynamometer test, the brake unit is certified to use for the aircraft trials of few landing. After successful feedback from the pilot, the brake unit is certified for limited life. After the life expiry, the brake unit is reexamined for the extension of the life.

4. CONCLUSIONS

In this report, we have described the essential elements in the design, development, and airworthiness certification of a typical military aircraft brakepad composite. We have recently developed the Fe/Si_3N_4/graphite composite brake pads for 8 MJ brake energy aircrafts. The steps involved in the development of this composite by the powder metallurgy, and testing involved in the proving its airworthiness are described in detail. Calculations of the brake dynamometer testing input parameters from the aircraft data are also presented. The results of the material level tests (microstructure, hardness, bend test, lab scale dynamometer), functional level tests (full scale dynamometer, static torque, brake fusing stop, taxi and parking tests), and aircraft and lifing trials of the composite showed that the composite is capable of providing excellent braking performance with 200 landing life for 8MJ braking energy applications. The success in the development and airworthiness certification of Fe/Si_3N_4/graphite composite is another milestone in the brake pad composite development for the country's military aircraft programs.

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