A small arc-heated plasma testing facility for thermal protection materials

Z. Q. Fu, H. J. Huang, W. X. Pan, C. K. Wu

Institute of Mechanics, Chinese Academic of Sciences, 100190, Beijing, China

Abstract: Experimental research on a 150 kW arc-heated plasma testing facility was conducted. Stable plasma jets with different gas compositions, temperatures and velocities were obtained at chamber pressure between 400 Pa – 100 kPa. Stagnation ablation experiments were conducted on samples of typical super alloys used for thermal protection systems. The microstructure and hardness of alloys before and after ablation were compared.

Keywords: plasma testing facility, stagnation ablation.

1. Introduction

Future concepts in high-speed flight such as those for space launchers, etc. will often consider sharp aerodynamic profiles for advantages in maneuverability, communication and drag reduction during flight [1]. However, such sharp profiles require particular attention to overall thermal management and protection [2]. The thermal protection materials (TPM) must exhibit desirable characteristics such as strength/stiffness at high temperature and high melt/oxidation temperature thresholds. For the qualification of TPM, simulation facilities are required which should offer high enthalpy conditions at pressure levels from the mbar-level up to more than one atmosphere for at least a few minutes [3]. However, conventional furnace oxidation study may not obtain meaningful results and testing conducted in large scale wind tunnel is very expensive. From this prospect, small scale plasma testing facilities, owing to its flexibility, simplicity, good controllability and cost efficiency, is more attractive. It is convenient to generate plasma with different gas compositions, velocities and temperatures. Although not applicable to testing of large components, such small scale plasma testing facilities are suitable to simulate local thermal environment, study the corresponding properties of materials and to better understand the principles of oxidation/ablation behavior.

In recent years, small scale plasma material testing facilities have been built to test the property of thermal protection materials (TPM) [3-5]. In this research, a 150 kW arc-heated plasma testing facility was built, aiming to attain high temperature properties of typical TPM samples under vacuum and positive pressure conditions up to 2 atm.

2. Experimental facility and method

The 150 kW arc-heated plasma testing facility is composed of several parts which include the plasma torch, parameter measurement system, sample-supporting and transmission system, power supply unit, buffer tank and vacuum system, water-cooling system and air supply system.

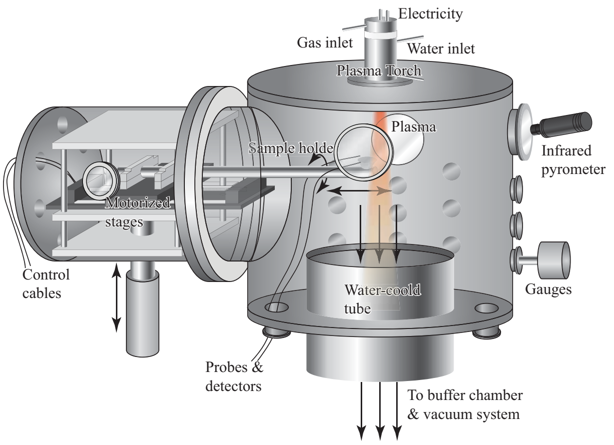


Fig. 1 Schematic of the main part of the 150 kW arc-heated plasma testing facility.

Fig. 1 is the schematic of the system. Samples to be tested are held on a multidimensional motorized stage. Temperature, pressure and heat flux probes/detectors were used to characterize the plasma jet. W_5-type thermocouples and an infrared pyrometer were adopted to monitor the temperatures on the rear and front surfaces of the samples respectively. The measurement range of the pyrometer is 700 – 2000 ℃. Time-dependent arc voltage, arc current, chamber pressure, temperatures etc. were recorded by a computer.

N_2 and N_2+O_2 are mainly used as the plasma gas with a total flow rate up to 630 slm. The measurement chamber was designed to be either operated in vacuum or in positive pressure up to 2 atm. Typical samples of TPM samples with the size of 50 × 50 × 1 mm were tested and their behaviors under different ablation conditions are compared.

3. Results and discussions

3.1 Characteristics of the plasma jet

Fig. 2 shows the photos of the arc plasma jets under conditions of different chamber pressures and gas compositions. Mach diamonds are clearly seen indicating supersonic flow in such situations.

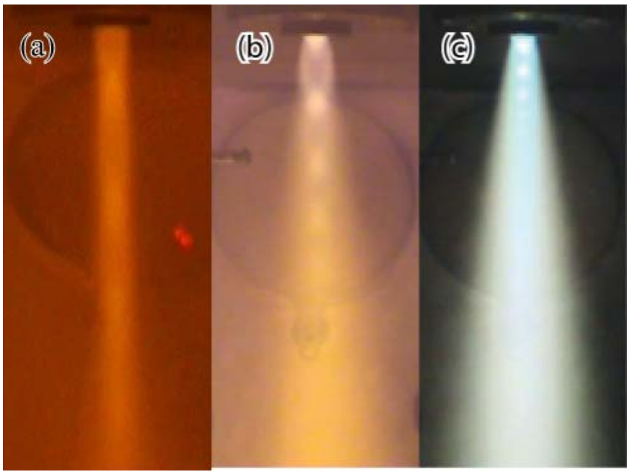


Fig. 2 Photos of plasma jets under different chamber pressures and gas compositions. (a) N_2, 1 kPa; (b) N_2, 10 kPa; (c) 20 %vol O_2-N_2, 30 kPa.

Fig. 3 shows the current-voltage characteristics (I-V curves) of the N_2 plasma with different gas flow rates at chamber pressure of 10 kPa. The increasing of the arc voltage with the gas flow rate is clearly seen. Otherwise, the arc voltage varies gently with the increase of the current when the gas flow rate keeps constant.

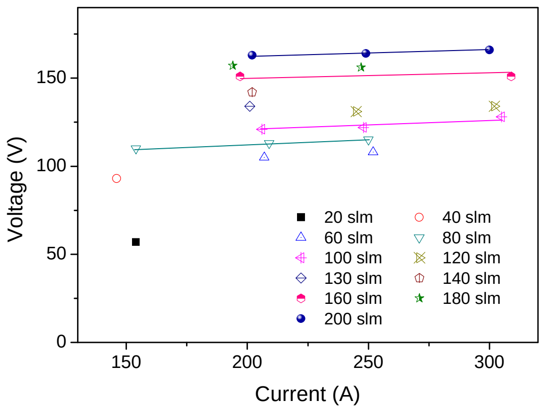


Fig. 3 I-V curves of the N_2 plasma with different gas flow rates.

Axial velocity distribution in a nitrogen plasma jet was extrapolated from the measurement of Mach angles. It is seen that along the central axis off the torch exit, the Mach number almost does not change with the value of 1.17 - 1.36 (**Fig. 4**).

Fig. 5 shows the dependence of the impact pressure on the gas flow rate measured at 10 mm off the torch exit with a chamber pressure of 2 kPa. A linear increase of the measured impact pressure with the increase of the total gas flow rate is seen. Because the Mach number is greater than 1, there is a detached shock before the probe, and the measured pressure does not represent the real total pressure. Using the Rayleigh formula, the stagnation-pressure before the shock can be deduced. In the Rayleigh formula, P_o is the stagnation pressure before the shock, P_o' is the stagnation-pressure after the shock, M is the Mach number and k is the ratio of specific heats. As the Mach number in the free plasma jet was measured to be 1.2 -1.4, the difference between P_o and P_o' is about 0.97.

$$\frac{P_o}{P_o'}=\left[\frac{2k}{k+1}M^2-\frac{k-1}{k+1}\right]^{\frac{1}{k-1}}\left[\frac{(k-1)M^2+2}{(k+1)M^2}\right]^{\frac{k}{k-1}}$$

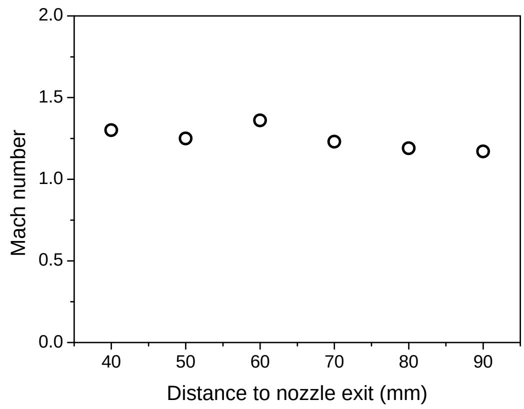


Fig. 4 Axial Mach number distributions in N2 plasma jet at 1 kPa.

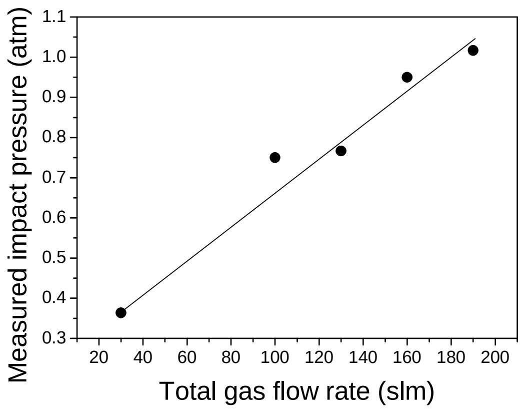


Fig. 5 Dependence of the measured impact pressure on the total gas flow rate.

3.2 Stagnation point ablation test of TPM

Stagnation point ablation test of TPM samples was conducted. The species of stainless steel and Ni-base alloy were placed on a water-cooled sample holder to simulate the service conditions where active cooling is used. The plasma gas was 20% vol O_2 + N_2 with a total gas flow rate of 100 slm.

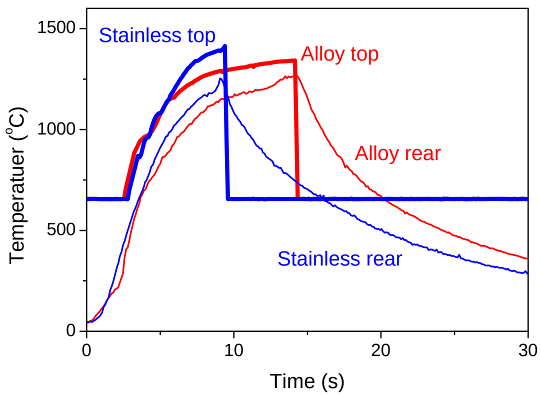


Fig. 6 Time dependent top and rear surface temperature of the TPM samples in the test. The samples were moved out of the plasma jet after the test, and the top surface temperature was no longer monitored by the pyrometer.

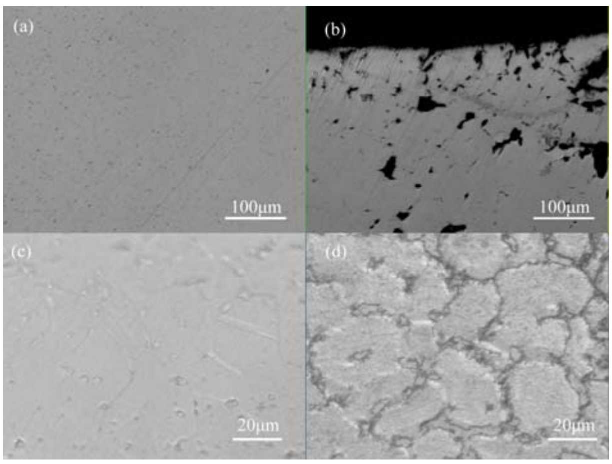
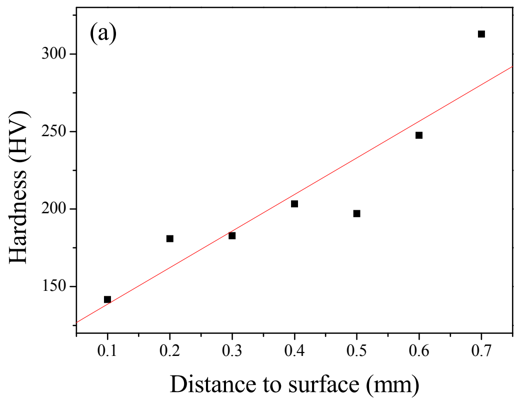


Fig. 7 Optical cross-sectional microstructures of the Ni-base refractory alloy before and after stagnation ablation test. (a) before ablation, not etched (b) after ablation, not etched (c) before ablation, etched (d) after ablation, etched.

With lower plasma input power of 20 kW, Ni-base alloy stands for 40 s with no obvious ablation. The top surface temperature increases to 880 ℃ and the rear surface temperature approaches the top surface temperature after 40 s. With a higher input power of 30 kW, both the top and the rear surface temperature of the sample increase much more rapidly. A central surface melting of the alloy specimen was observed after 10 s and for the stainless sample, 5 s test results a big hole in the center. **Fig. 6** shows the revolution of the top and rear surface temperatures of the different samples. The samples were moved out of the plasma jet after the test, and the top surface temperature was no longer monitored by the pyrometer, resulting the sudden drop of the top surface temperature curve.

With the same plasma jet condition of 30 kW input power, the sample with 200 μm YSZ coating was also tested. Compared to the sample without coating, the coated sample is much more durable. No obvious change of the sample can be seen except that the color of the coating becomes whiter because of the oxygen penetration.

Fig. 7 (a) and (b) show the microstructure change of the alloy sample after 10 s test with the input power of 30 kW. In order to show the microstructure more clearly, a chemical etching with 20min in the solution of 2.5g $FeCl_3$, 20ml CH_3CH_2OH and 5ml HCl was performed for the two samples. Results are shown in **Fig. 7** (c) and (d) as a reference.



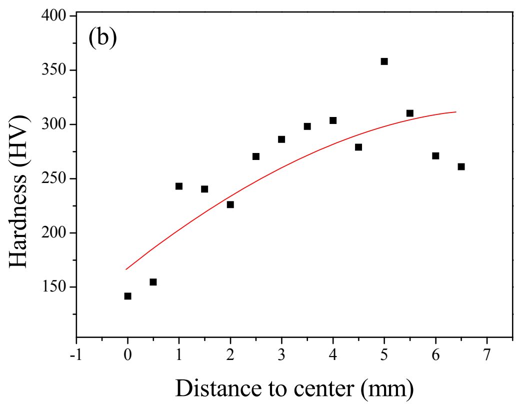


Fig. 8 Micro Vickers hardness distributions of Ni-base alloy samples after test. (a) along the thickness direction; (b) along the surface direction.

It can be found from **Fig. 7** (b) that many cavities appear near the center of the ablation region of the sample. On one hand, these cavities may be caused when the center of the sample was nearly melted in the plasma jet and then quickly cooled down after being moved out of the plasma jet. On the other hand, some composites of the sample might be burned out, which also leads to the cavities. Compare **Fig. 7** (c) and (d), it is seen that the sample after test is more easily etched than before, especially the grain boundaries become much weaker after the ablation test.

Micro Vickers hardness test was also performed on the samples. The load was 100 g and the keeping time was 15 s. The hardness distributions along surface and thickness directions from the center of the sample are shown in **Fig. 8** (a) and (b). In **Fig. 8** (a), the measured hardness increases from 141HV near the top surface to 312HV near the bottom surface, which almost equals to the hardness of the sample before ablation. **Fig. 8** (b) is the surface hardness distribution. With the distance from the center increasing, hardness also grows correspondingly.

4. Conclusion

Small arc-heated plasma testing facility for thermal protection materials can conveniently produce stable plasma jets with adjustable gas compositions, temperatures and velocities. Therefore, it can be used to simulate local thermal environment for thermal protection materials of space vehicles and do research on ablation characteristics of materials. Preliminary experiments of stagnation ablation on Ni-base refractory alloys were carried out. It is concluded that Ni-base refractory alloys can withstand severe ablation better than stainless steel, and YSZ coating is helpful to improve the thermal protection ability of the sample. Further quantification of test conditions and test results will be done in the future.

Acknowledgement

This work is supported by the National Natural Science Foundation of China under Grant Nos. 50702064 and 10621202.

References

[1] Scatteia L, Riccio A, Rufolo G, Filippis F D, Vecchio A D and Marino G 2005 AIAA 2005-3266

[2] Jackson T A, Eklund D R and Fink A J 2004 *J MATER SCI*. **39** 5905

[3] Auweter-Kurtz M 2002 *Vacuum*. **65** 247

[4] Fujita K, Mizuno M, Ishida K and Ito T 2008 *Journal of Thermophysics and Heat Transfer*. **22** 685

[5] Bottin B, Carbonaro M, Chazot O, Degrez G, Abeele D V, Barbante P, Paris S, Van Der Haegen V, Magin T and Playez M 2004 *Contributions to Plasma Physics*. **44** 472