Anodic arc evaporation of graphite for deposition of ta-C diamond-like films

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Context

Tetrahedral amorphous carbon (ta-C) is one of the most interesting modifications of the "Diamond-like Carbon" (DLC) materials. The tetrahedral coordinated amorphous carbon phase without hydrogen content is characterized by several special properties, which include extremely high hardness between 40 and 80 GPa, high thermal stability in oxygen atmosphere up to 550 °C, high thermal conductivity, inert chemical properties, and extremely low friction coefficients between 0.1 and 0.15. It is well known that in ta-C films the atomic bonding is mainly based on sp^3 hybridization with tetrahedral three-dimensional arrangement of carbon atoms resulting in diamond-like bonding and high hardness. Various processes for the deposition of ta-C layers have become known, including the filtered cathodic arc discharge, the pulsed high-current arc discharge and the laser steered cathodic arc process. These processes have in common that the arc discharge burns on a graphite electrode connected as a cathode. The cathodic arc processes produce highly ionized carbon vapor, resulting in relatively high energies of the layer forming carbon particles. Nevertheless, the characteristic droplets and particles that get mixed into the vapor stream are problematic in arc processes with evaporation from a graphite cathode. The anodic arc evaporation - originally developed for evaporation of transparent conducting oxides (TCO) [1] - was applied for deposition of ta-C coatings [2]. Main results are presented here.

Experimental - Anodic arc evaporation in combination with a hollow cathode arc discharge

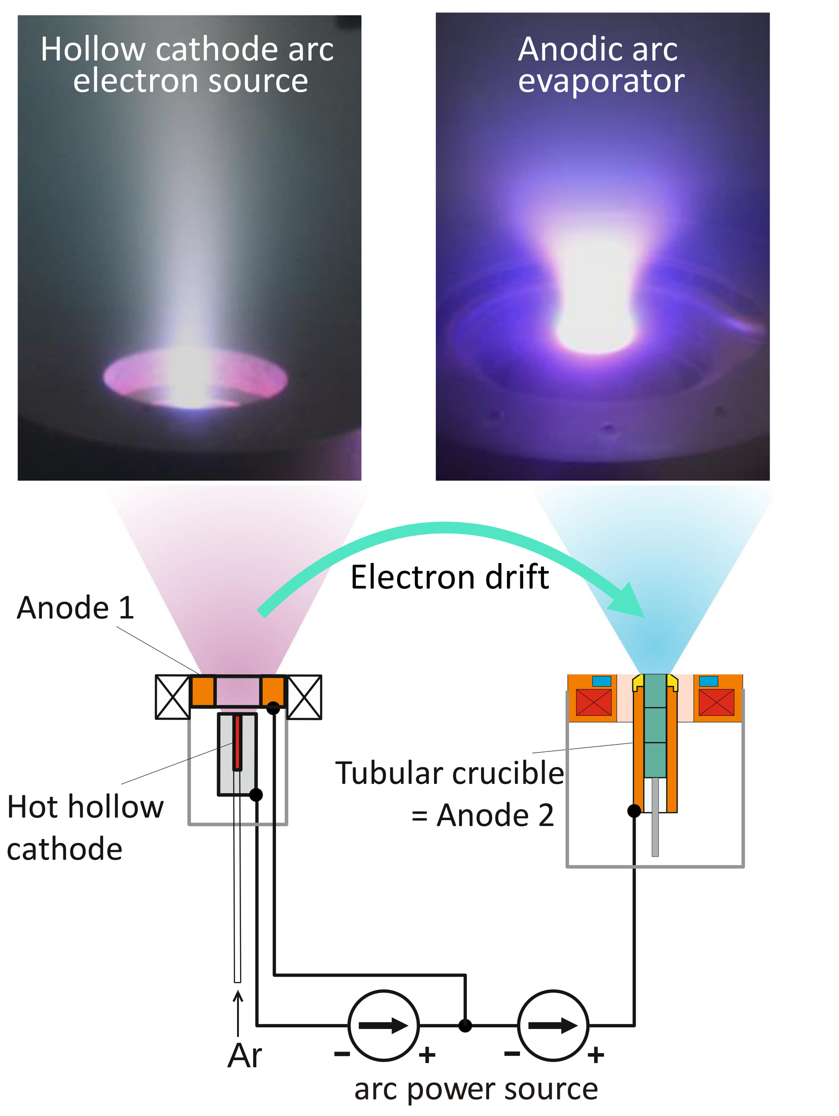

Fig.1 Principle and electrical circuit of the anodic arc evaporation in combination with a hollow cathode

- Graphite rod diameter 10 mm
- Graphite hard felt (Sigratherm, SGL)
  - Heat insulation,
  - Electrical connection
- Magnetic system
  - Contracts the discharge
  - Shielding anode parts
  - Magnetized plasma
- Motor driven feeding
- Electrically insulated housing
- Anode 2 current: 100-200 A

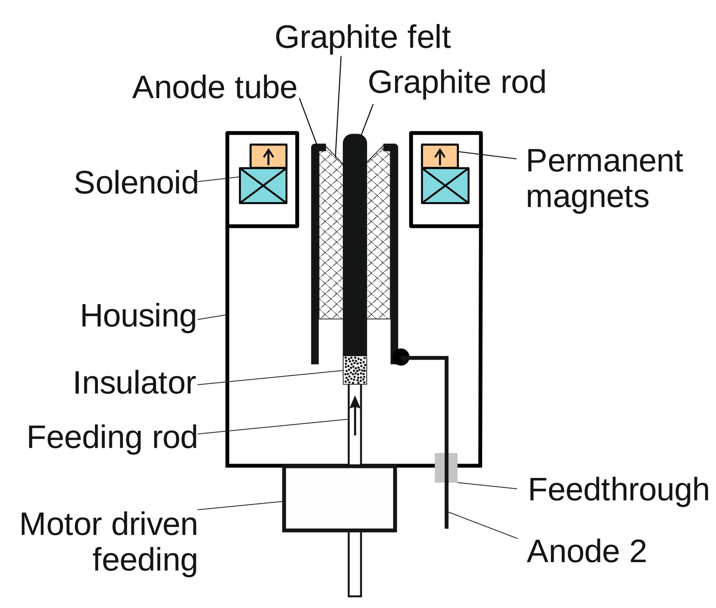

Fig.2 Scheme of the graphite evaporator

Fig. 3
Hollow cathode arc plasma source LAVOPLAS, 50 - 200 A

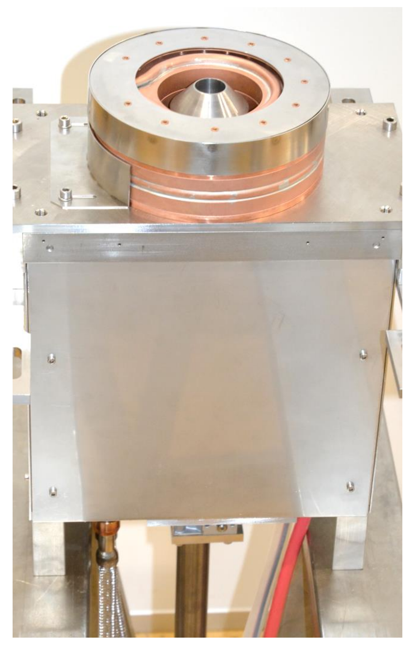

Fig. 4
Anodic arc evaporator 0 - 200 A, max. 20 kW

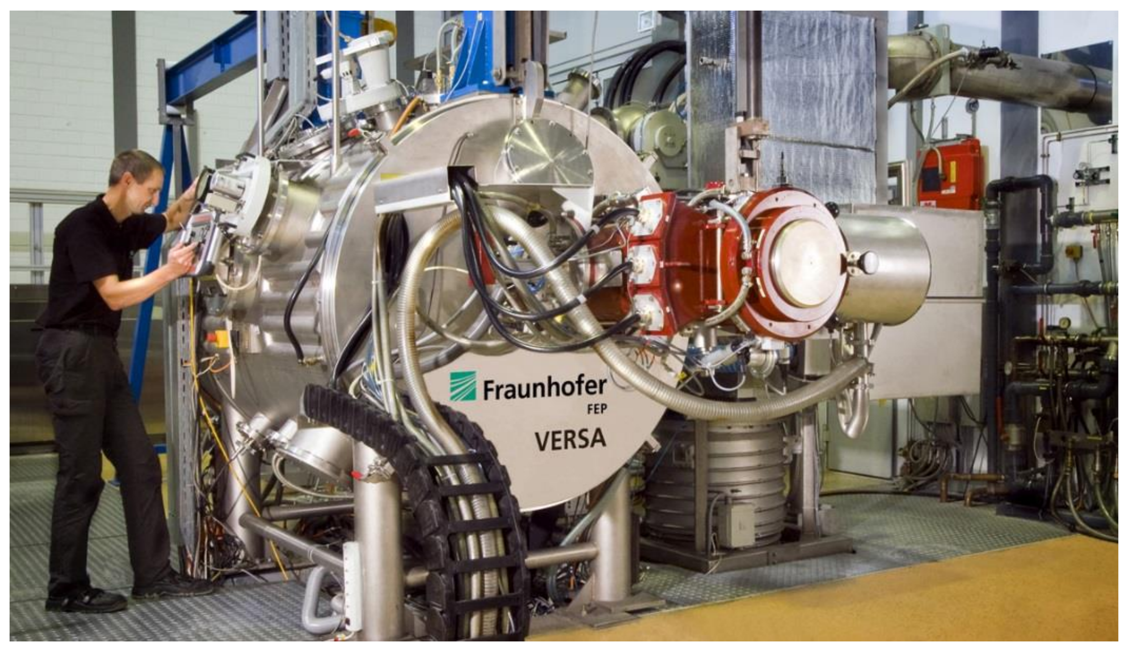

Fig. 5
High-vacuum equipment "VERSA" (plasma sources, EB-PVD, PECVD, Sputtering, thermal evaporation, glove box loading chamber)

Properties of the plasma process [1, 2]

- Hollow cathode arc discharge as electron source
- High ionization degree of the carbon vapor (~ 100 %)
- **High deposition rate** 4 – 18 nm/s (static @ distance of 25 cm)
- Stable operation due to material feeding
- Modular design of evaporator
- Side by side arrangement for large area coating possible

Results - Properties of deposited ta-C coatings

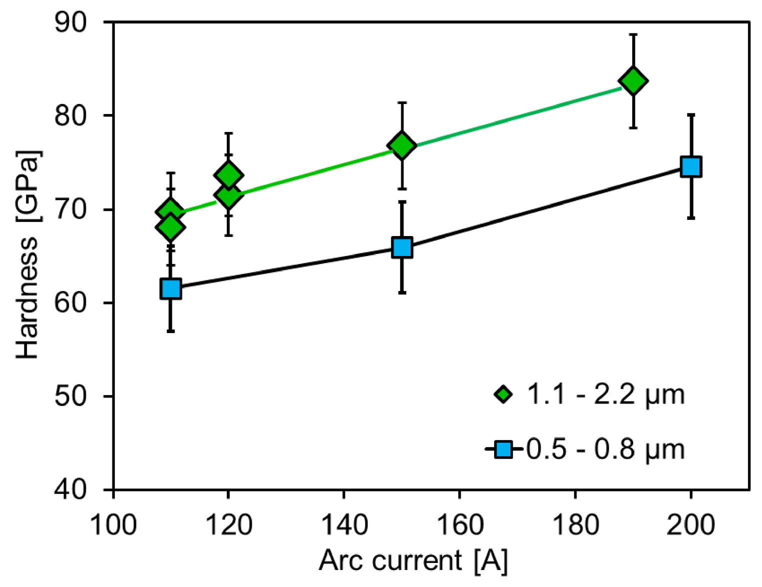

Fig.6 Layer hardness measured by nanoindentation plotted over arc current, parameter: DLC layer thickness

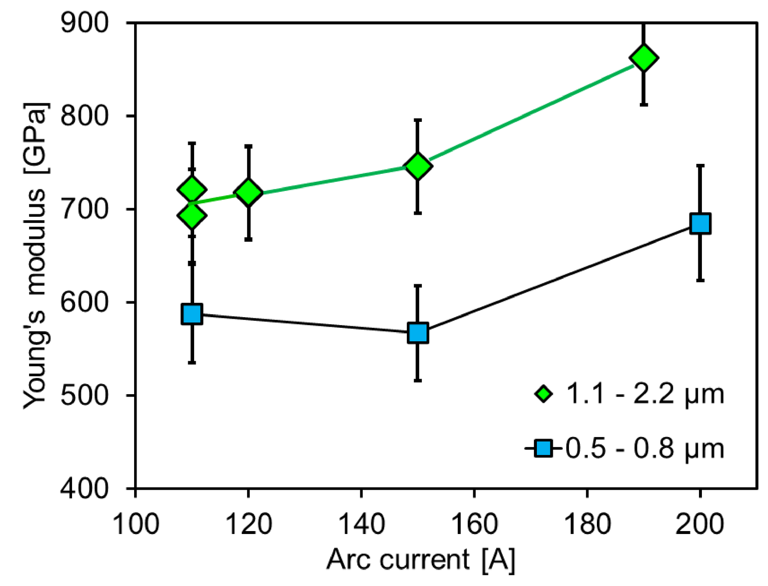

Fig.7 Young's modulus measured by nanoindentation plotted over arc current, parameter: DLC layer thickness

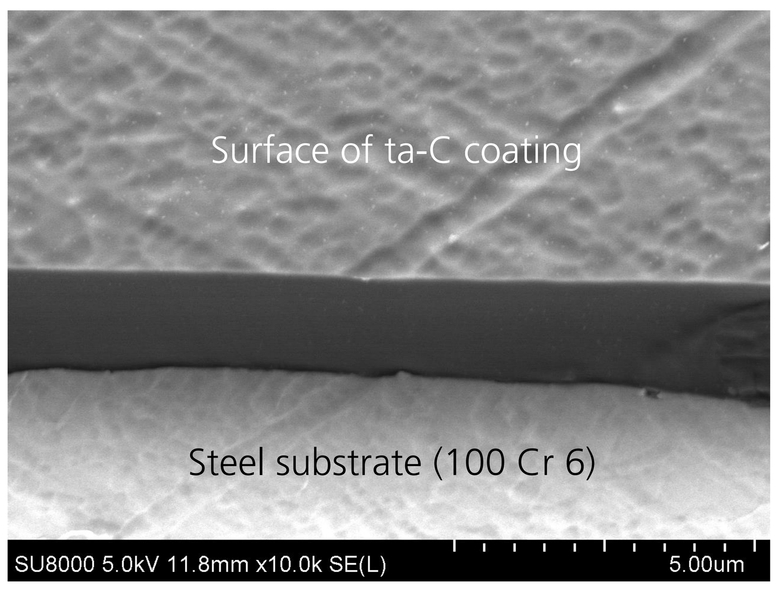

Fig.8 Cross fracture and surface of a ta-C layer deposited @ a rate of 13 nm/s without droplets

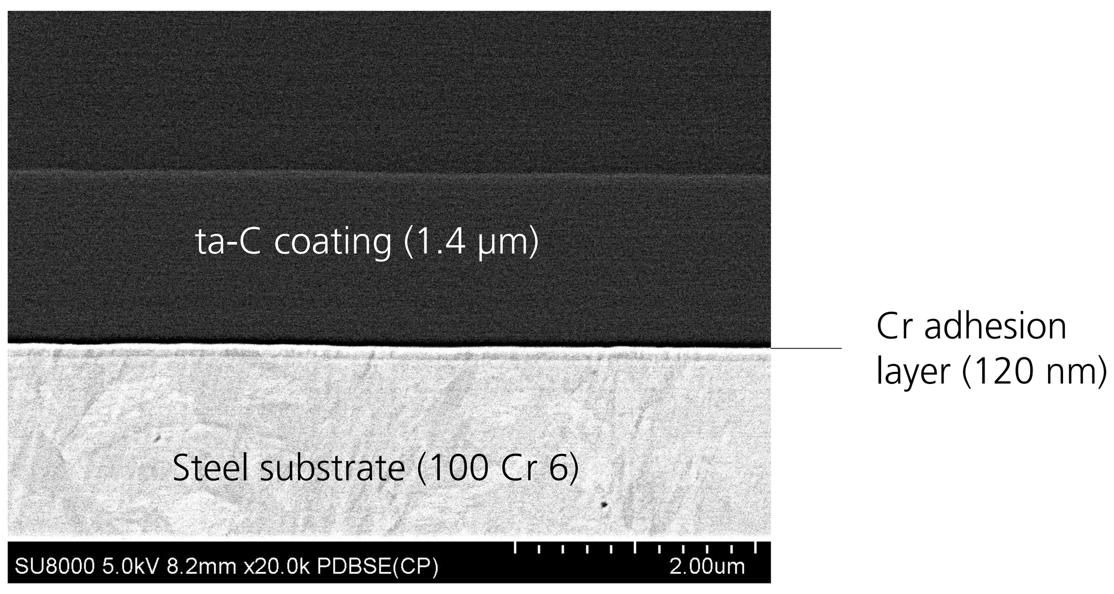

Fig.9 Cross section through a coating system with a Cr adhesion layer for mechanical and wear tests

Properties of the ta-C coatings [2]

- **No droplets** as typical for the cold cathode arc
- Good layer adhesion
- **High hardness** 61 – 83 GPa (Nanoindentation)
- High Youngs modulus 588 – 860 GPa (Nanoindentation)
- High sp^3 content 70 – 88 % (Raman spectroscopy)
- Highest hardness values possible without external bias

Summary and Outlook

The anodic arc evaporation in combination with a hollow cathode arc discharge is a very intensive plasma deposition process and has been used to deposit hydrogen-free carbon films by graphite evaporation. By applying a bias voltage, the particle energies can be increased and the layer properties customized. Even without bias, the films have proven to be very hard and were characterized by nanoindentation, Raman spectrometry, FE-SEM, AFM and spectroscopic ellipsometry. The films deposited at substrate temperatures < 200°C are very hard (61-83 GPa) and have a high Young's modulus (588-860 GPa). The Raman spectra indicated a significant presence of tetrahedral sp^3 bonds, ranging from 70 to 88%. The coatings are very smooth and were found to be droplet-free, as confirmed by FE-SEM and AFM. The deposition rates of 4-18 nm/s are remarkably high for tetrahedral amorphous carbon (ta-C) coatings, making them a promising option for industrial applications. The ta-C coatings exhibit very high hardness and a smooth surface, making them ideal for wear-resistant coatings.

The anodic arc evaporation was already successfully applied to the evaporation of metals and such as Magnesium (Mg), Chromium (Cr), semiconductors such as Silicon (Si), ITO, IZO and AZO as well as compounds such as Tin oxide (SnO_2) and Cesium iodide (CsI). Due to the combination of high ionization degree, high deposition rate and droplet free evaporation the process has a high potential for further applications and other coating materials. The deposition process is set to be scaled up using a side-by-side arrangement for large-area coating.

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[1] B. Scheffel, O. Zywitzki, T. Preußner, T. Kopte, Thin Solid Films, Vol. 731, 2021,138731, DOI 10.1016/j.tsf.2021.138731.
[2] B. Scheffel, O. Zywitzki, T. Kopte, Surf. Coat. Technol. Vol. 477, 2024, 130305, DOI 10.1016/j.surfcoat.2023.130305.

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