

RESEARCH AND DEVELOPMENT OF NOVEL ADVANCED MATERIALS FOR NEXT-GENERATION COLLIMATORS*

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Abstract

The study of innovative collimators is essential to handle the high energy particle beams required to explore unknown territory in basic research. This calls for the development of novel advanced materials, as no existing metal-based or carbon-based material possesses the combination of physical, thermal, electrical and mechanical properties, imposed by collimator extreme working conditions. A new family of materials, with promising features, has been identified: metal-diamond composites. These materials are to combine the outstanding thermal and physical properties of diamond with the electrical and mechanical properties of metals. The best candidates are Copper-Diamond (Cu-CD) and Molybdenum-Diamond (Mo-CD). In particular, Mo-CD may provide interesting properties as to mechanical strength, melting temperature, thermal shock resistance and, thanks to its balanced material density, energy absorption. The research program carried out on these materials at CERN and collaborating partners is presented, mainly focusing on the theoretical investigation, material characterization and manufacturing processes.

INTRODUCTION

The LHC collimation system is to ensure reaching nominal and ultimate machine performances by intercepting and safely absorbing high intensity losses at an unprecedented level [1]. To do so, a staged approach has been devised: while Phase I collimators were designed to guarantee maximum robustness against abnormal beam losses, future Phase II collimators are to overcome Phase I limitations, which may limit LHC performances, in terms of cleaning efficiency, RF impedance and radiation hardness [2]. One of the keys to successfully meet such challenging requirements lays in the use of innovative materials for the collimator jaws, combining a wide range of physical, thermal, mechanical and electrical properties.

With this goal in mind, CERN has launched an ambitious R&D program, partly within the EuCARD collaboration [3], with the involvement of several partners from the academic, technology and industrial sectors.

MATERIAL CLASSIFICATION

In order to classify and rank relevant materials against a number of key requirements, five main figures of merit were identified.

- Atomic number Z provides a rough indication of the material cleaning efficiency. The higher the atomic number, the better the cleaning efficiency.
- Electrical conductivity γ . This parameter has to be maximized in order to limit RF impedance.
- Steady-state Stability Normalized Index (SSNI), defined as $k/(\alpha\rho)$, (k thermal conductivity, α Coefficient of Thermal Expansion, ρ density). SSNI provides an indication of the ability of the material to maintain the geometrical stability of the jaw when submitted to steady-state losses.
- Transient Thermal Shock Normalized Index (TSNI), defined as $[R(1-v)c_{pv}]/(E\alpha\rho)$ (R mechanical strength, v Poisson's ratio, c_{pv} volumetric heat capacity, E Young's modulus). TSNI is correlated to the highest absorption rate of impacting particles before the onset of mechanical damage.
- Melting Temperature T_m provides an indication of the maximum temperature the material can achieve before being permanently damaged by melting.

Unlike previous proposals [3], both SSNI and TSNI are normalized by the material density. This is done to take into account the influence of nuclear properties on the deposited energy distribution: high density materials are penalized as they have shorter interaction lengths with more peaked depositions (higher damage potential). Manifestly, this conflicts with the high cleaning efficiency requirement calling for higher density materials.

Table 1: Relevant properties and figures of merit for selected materials at RT (T_m of Metal-CD is referred to the metallic matrix)

	C-C	Glidcop	Mo	Cu-CD	Mo-CD
ρ [kgm ⁻³]	1650	8900	10220	~5400	~6900
α [10 ⁻⁶ K ⁻¹]	1.5	16.6	5.3	6 ÷ 7	4.5 ÷ 6
k [Wm ⁻¹ K ⁻¹]	60	365	140	490	185 ÷ 220
Z	6	29	42	~11.4	~17.3
γ [MSm ⁻¹]	0.14	53.8	19.2	12.6	9.9
SSNI [kWm ² kg ⁻¹]	24.2	2.5	2.6	13.1 ÷ 15.3	6.9 ÷ 10.9
TSNI [kJkg ⁻¹]	793	35	55	44 ÷ 51	72 ÷ 96
T_m [°C]	3650	1083	2623	1083*	2623*

Figures of merit along with some key material properties are reviewed in Table 1 for some reference materials such as carbon-reinforced carbon composite (C-

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C), used for Phase I collimators, molybdenum and Glidcop® (a dispersion-strengthened copper) and for the two most promising metal-diamond composites (Cu-CD and Mo-CD). For these two materials, target values and ranges are provided.

Table 1 shows how C-C still remains by far the best material in terms of thermo-mechanical performances; however, its poor electrical conductivity turns into high RF impedance [5], potentially leading to instabilities of the LHC at nominal/ultimate intensities. Its low Z makes it also less desirable as to cleaning efficiency. Mo has low CTE and good electrical conductivity, but its high density would lead to excessive deposited energy densities. Conversely, metal-diamond composites are particularly appealing for their balanced compromise between thermal stability and thermal shock indexes, electrical conductivity, density/atomic number.

Mo-CD, in particular, is very interesting for its high melting point and thermal shock index, making it very attractive to limit the effects of elevated temperatures and stresses in the regions submitted to high intensity impacts.

CU-CD DEVELOPMENT

Copper-Diamond, developed by the Austrian Institute of Technology (AIT now RHP-Technology) [6], has been the first advanced material considered.

The material has been obtained by Rapid Hot Pressing (RHP) of metallic Cu, with the addition of small quantities of boron powder, mixed with small synthetic diamonds (CD): the RHP technique permits to solid-sinter in controlled atmosphere the mixture of powders applying a controlled pressure and temperature cycle, up to roughly 1000 °C.

This process permits to achieve very good compaction rates (~95%), without diamond graphitization (this phenomenon starts becoming significant at ~1300 °C).

Since no chemical affinity exists between Cu and CD, adhesion must be assured by a third element, in this case Boron. B particles form carbides at the diamond interface and slightly dissolve in Cu, assuring mechanical bridges between the two main phases (Fig. 1).

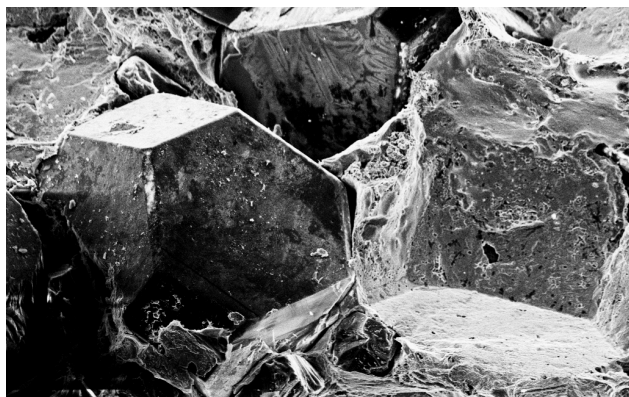


Figure 1: SEM picture of the fracture surface of Cu-CD. The synthetic diamonds are embedded into the Cu matrix, which detached during fracture (small boron bridges still attached to diamonds can be observed).

This interface has however inherent limitations due to the brittleness of Boron Carbides and to the limited contact surface between Cu and CD, obstructing heat transfer.

Notwithstanding this, Cu-CD still represents an interesting candidate for future collimators (specially should geometrical stability become a key requirement), although Cu fairly low melting point somehow limits its application for highly energetic accidents.

MO-CD DEVELOPMENT

Besides EuCARD collaboration, CERN is carrying out with a SME (BrevettiBizz, Verona, Italy) a further R&D program on Molybdenum-Diamond composites [7]. The objective of this program is to obtain a composite material combining good thermal and mechanical properties on a broad range of temperatures with a tailored density and acceptable electrical resistivity.

As opposed to Cu, Mo forms stable carbides (MoC) on diamond surface which provide good bonding strength: since MoC has low thermal conductivity and high brittleness, the carbide layer must be kept as thin and homogeneous as possible.

Mo-CD is also obtained by RHP technique. Given that the temperature needed to fully sinter Mo (~1700 °C) is much higher than for Cu, diamond degradation constitutes the main challenge of the process.

To reduce sintering temperature to an acceptable level (1200-1300°C), while keeping good compaction rates, two different approaches have been tested:

- Liquid Phase Sintering (LPS): a third low-melting phase (typically Cu or Cu-Ag) is added to the mixture to fill in the pores between Mo and CD.
- Assisted Solid-state Sintering (ASS). The addition of small amount of activating elements (typically Ni or Pd) permits to reduce Mo sintering temperature.

Liquid Phase Sintering

Many different combinations of powders, with various liquid phase fillers and diamond coatings have been tested at CERN. Samples with dimensions ranging from a few millimetres thickness to 400x80x20 mm³ (a size comparable to collimator jaw) were produced. Values of flexural strength for 13 different compositions are reported in Fig. 2.

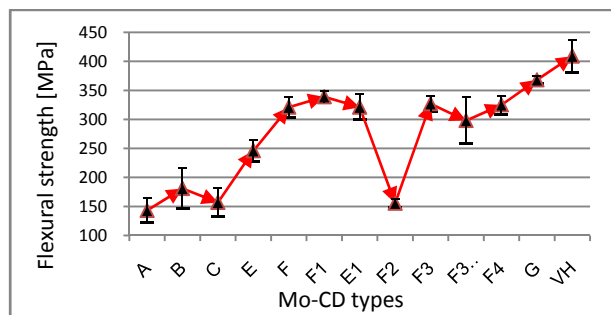


Figure 2: Flexural Strength of Mo-CD compounds with different liquid phase elements and CD coatings.

Assisted Solid-state Sintering

The addition of small amounts of activating elements, such as Ni or Pd, brings a significant increase in Mo sintering. Pd was eventually preferred to cheaper Ni as the latter forms a brittle inter-metallic phase (MoNi) with a low melting point. Pd, unlike Ni, is completely soluble in Mo matrix up to 3% in weight, with no secondary phase formation. Mo-Pd compounds were successfully sintered at temperatures as low as 1300 °C.

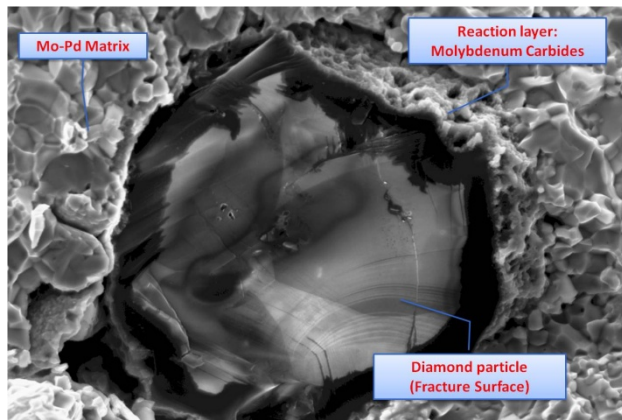


Figure 3: SEM picture of Mo-Pd-CD. Note the formation of MoC at the diamond-matrix interface.

However once CD is added, the presence of diamond large stiff particles interferes with the plastic deformation of Mo in the region near diamond surface limiting the compaction rate (Fig. 3).

A large R&D effort is being done to improve these weaknesses. MoCD remains one of the most promising materials for Phase II applications.

AG-CD DEVELOPMENT

A third metal-diamond composite, Silver-Diamond, developed at EPFL by Liquid Infiltration technique [8] has been investigated within the EuCARD collaboration.

Ag-CD (with 3% Si) exhibited very good properties, thanks to the formation of Silicon Carbides on diamond surfaces, as well as very good thermal properties.

However several drawbacks, such as Ag low melting point (840°C) and non-homogeneity of diamond content, complicate its use for Phase II collimators.

RADIATION HARDNESS

During their operational life, collimators will be exposed to very high radiation doses, with likely degradation of thermal, electrical and mechanical properties of jaw materials. Two EuCARD partners (RRC – Kurchatov Institute and GSI) are involved in the assessment of irradiation damage induced in Phase II candidate materials. Studies are ongoing; preliminary results from GSI on Cu-CD show no trace of debonding at the Cu/CD interface. However, evidence of defects in diamond lattice has been found: in-depth investigations are still in progress [9].

CONCLUSIONS

The R&D program aimed at studying, developing and testing advanced materials for LHC Phase II Collimators is progressing: the challenge of producing metal-diamond composites with convenient dimensions and homogeneity has already been met.

Material properties are systematically measured with specific physical, thermal and mechanical tests. For most interesting composites, these are to be complemented by irradiation damage assessment and, eventually, by particle beam tests under extreme conditions [10].

A broad range of compounds has been produced, including Cu-CD, Mo-CD and Ag-CD. The R&D program is far from being complete; however properties of these materials are already fulfilling some of the target values which were set through specific figures of merit.

Cu-CD and Mo-CD are, so far, the most interesting materials. In particular, Mo-CD development seems to open the way towards a material for high-temperature applications requiring balanced density and good thermal shock resistance.

ACKNOWLEDGEMENTS

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