ARMORED ELEMENTS BY MEANS OF POWDER METALLURGY: APPLIED STRESSES, FRACTURE MECHANISMS AND SURFACES

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Abstract

The main aim of this work is to demonstrate the inter-dependencies between chemical composition, mechanical properties and fracture mechanisms to high-speed impacts of a selected series of P/M products. Materials tested have been designed to withstand the stresses produced by ballistic impacts, and processed by powder metallurgy techniques, producing two systems. The compositions were based on Distaloy AE and Astaloy CrL as main powders.

The sintering treatment has been carried out in vacuum furnace, following the debinding phase done by the use of a dedicated furnace filled by nitrogen atmosphere. After sintering, the obtained samples had been tempered, using a cycle integrated to sintering. Characterizations were focused on assessment of fracture surfaces, microstructures, quantification of impact energy, hardness and density, followed by evaluation of the behaviour of the materials obtained towards high speed stresses connected to ballistic impacts.

Keywords: fracture surfaces, microstructure, ballistic, bullet, high speed

INTRODUCTION

Armour materials, commonly produced by rolling, are designed to offer extreme deformation in order to dissipate energy from the ballistic impact. Alloying elements are generally added to improve the strength, and to give the material some additional properties, i.e. weldability. Moreover, the microstructure of these material is usually austenitic-martensitic, to obtain very high mechanical properties through the distortion forced to the crystal lattice [1-5].

The typical standard used to classify the bullet resistance is UNI-EN 1522, and the sorting of the different classes is based on thickness of the plate, energy and type of bullet. As a first improvement for standard materials, ceramic-reinforced armours have been introduced, due to the good weight/performances balance. Nevertheless, this approach revealed to be unsatisfactory with respect to the more specialized ammunitions that have been developed during the years. More complex structures have been designed coupling several layers, to give different properties to the material. Other improvements are given by multi-layer protections designed pairing metallic and ceramic layers (laminated composites) to improve the resistance of the material to armour-piercing bullets [6-10]. It is evident that the cost of more complex protection systems is very high, as well as technical difficulties related to the production of complex shapes. The powder metallurgy approach proved to be a possible way to produce complex shapes with a convenient cost/performances ratio, and

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the chance to give to the material special features related to resistance toward ballistic impacts has been investigated in [11]. Materials obtained by P/M routes showed some different mechanisms assigned to the dissipation of energy derived from the impact, with regards to the common typologies related to rolled materials.

The objective of this work was to produce and characterize materials able to withstand stresses derived from ballistic impacts. The task was focused, in the first part, on the selection of powders to be used. It was observed that different amounts of alloying elements to the main powder can influence the resistance of the material obtained. To set up the systems to be analyzed, the approach used was to produce a first mix, created by the use of the main powder (Distaloy AE) and admixed graphite, and a second one, based on an evolution of what investigated in [11], but set up on a different main powder and with admixed elemental Nickel powder.

Furthermore, the adopted processing conditions were directed to the maximization of mechanical properties. High pressure compaction and high temperature sintering were adopted, to maximize the carbon diffusion and the bonding of particles, improve the properties and reduce the porosity that acts as a detrimental contribution to the mechanical resistance. This aspect is mandatory, since being the porosity still present in the parts, it must be controlled to minimize its detrimental effects on the mechanical properties. Moreover, the pores should take a round shape, to be more inclined to dissipate energy by plastic deformation, in spite of cracking [12]. In this paper, the successful application of P/M for the production of armours has been investigated, and the assessment was focused on the interconnections between ballistic resistance and mechanical properties.

EXPERIMENTAL

The compositions of the main powders used are resumed in Table 1.

Tab.1. Summary of chemical composition of the main powder used.

Name	Cu [%]	Ni [%]	Mo [%]	Cr [%]
Distaloy AE	1.5	4.0	0.5	-
Astaloy CrL	-	-	0.2	1.5

With respect to the systems produced, the compositions are reported in Table 2.

Tab.2. Summary of compositions formulated.

Name	Composition
A	Distaloy AE (99.50$\%_{wt}$) + Graphite (0.50$\%_{wt}$)
B	Astaloy CrL (95.60$\%_{wt}$) + Ni (4.00$\%_{wt}$) + Graphite (0.40$\%_{wt}$)

For all the systems, the percentage of lubricant (0.65$\%_{wt}$) added is referred to the 100% of powder. The mixing phase has been realized using a Turbula mixer, for 20 minutes. With respect to the pressing, a hydraulic machine, capable of 2MN, has been used, equipped with standard 10x10x55 mm die (Charpy test) and standard Φ40x5 mm die (ASTM G99). The compacting pressure used to produce all the specimens, for the two systems, was 700 MPa. The debinding phase was performed in a dedicated Nabertherm N120 furnace, at 550°C for 60 minutes, using a continuously filled nitrogen atmosphere. The sintering phase has been executed at 1240°C, for 1 hour. This treatment has been carried out in vacuum furnace, by a sinter-hardening approach, switching to rapid cooling directly from the sintering temperature. A pressurized flow of Nitrogen gas was used to obtain the hardening, with a cooling rate of -3°C/s. Finally, the integrated tempering phase was realized at 200°C, for 2 hours. To set up the impact energy (Charpy) test, samples of standard dimensions (10x10x55mm) were produced. With respect to the purpose of ballistic test, specimens were created using the Φ40x5 mm tool, set to produce discs 13 mm in thickness. The evaluation of resistance to stresses inducted by bullets engaging the sample at high speed, has been executed using a M14 Rifle, chambered in .308W caliber, loaded with handloaded ammunition, to provide consistent accuracy and repeatability.

RESULTS

Values obtained from mechanical characterization are resumed in Table 3.

Tab.3 Summary of mechanical properties.

Name	Green d.[g/cm^3]	Sintered d.[g/cm^3]	I.E. [J/cm^2]	Hardness [HRA]
System A	7.21	7.22	35.4	85.3
System B	7.14	7.24	25.9	79.6

Starting with densities, system A provided the best green density, whereas system B was proper of the maximum density as sintered. About the Impact Energy (I.E.) obtained, system A has shown the best impact resistance. The system B was capable of a lower value of I.E. with respect to system A. This is due to different fracture mechanism, since Ni admixed in system B is producing some wide areas, rich in this element, able to influence the ductility of the material. The diffusion bonded Ni of system A results to be more adequate to provide a higher value of I.E on the studied mixes. Results obtained from the hardness test, reported similar values. Nevertheless, system A showed slightly higher hardness, due to the influence of the increased amount of graphite on the microstructure [13-14]. This effect is noticeable analyzing differences between pictures reported as Fig.1 and Fig.2. The structures of both the systems are similar, and made of martensite and bainite, with some white areas identified as austenite, corresponding to Nickel rich phases. Since the chemical composition is quite similar between the two materials, also the microstructure is mostly similar, but the areas rich in Nickel are, for system B, larger, due to the admixing of the elemental powder related to that composition, in spite of having Nickel added as an alloying element before diffusion bonding of powder.

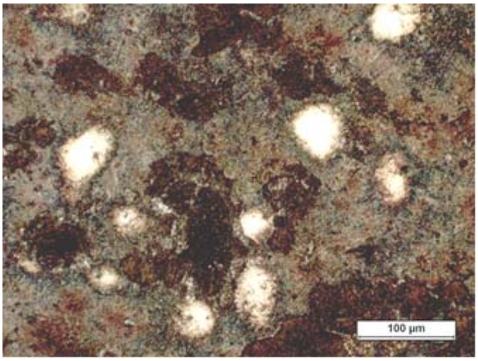

Fig.1. Microstructure of system A, 200x.

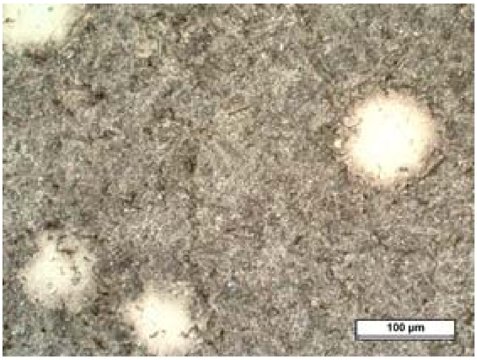

Fig.2. Microstructure of system B, 200x.

The Ballistic test

The ballistic test was carried out using a special supporting system designed to avoid any interference to the free deformation of the sample. A thin ring is machined into the support to withstand the forces related to impact only on the circumference, avoiding that the support itself could have any kind of interference during the test. The structure was set up to guarantee the perpendicularity of the surface of the samples to the direction of the bullet. One bullet for each sample has been shot. The assessment of the specimens resulting from ballistic test was focused on investigation of cracks and other anomalies on the surface that could suggest the impending failure of material.

Fig.3. Sample after ballistic test, system A.

Fig.4. Sample after ballistic test, system B.

None of the samples tested resulted broken as a consequence of the ballistic impact. The specimens recollected after the test showed significant plastic deformation with respect to the surface directly hit by the bullet, exhibiting a smooth dent. No cracks have been developed as a result of high speed-high pressure impacts, and no cavity has been produced afterwards the stress. Nevertheless, the main difference observed between the mixes tested has been found to be the depth of the dent created, measured to the lowest flat point using a Mitutoyo gauge equipped with a rod dedicated to the measurement of hollows. System A, providing higher impact energy, exhibited a depth of about 0.45 mm, in spite of System B, that showed a depth, with respect to the impact of the bullet, of about 0.55 mm.

Investigation of fracture surface

The investigation of fracture surfaces has been carried out using Leo SEM microscope and focused on determination of fracture mechanism. Samples from I.E. test were used.

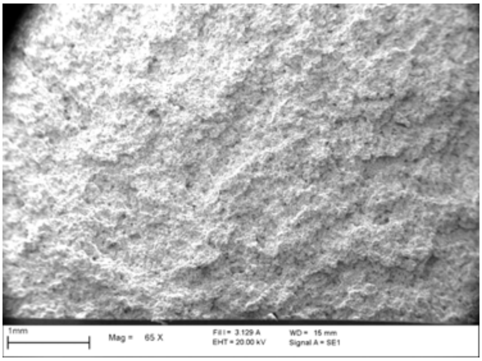

Fig.5. SEM image, system A, 65x.

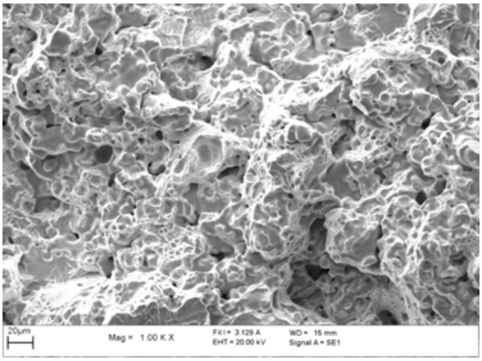

Fig.6. SEM image, system A, 1000x.

The assessment at low magnification of the fracture surfaces from system A, revealed an overall brittle mechanism. The fracture showed a flat geometry, with consistent micro-dimples located on the entire area. On higher magnification, the micro-dimples appeared to be well distributed on the surface, pointing out the successful mixing and sintering of powders.

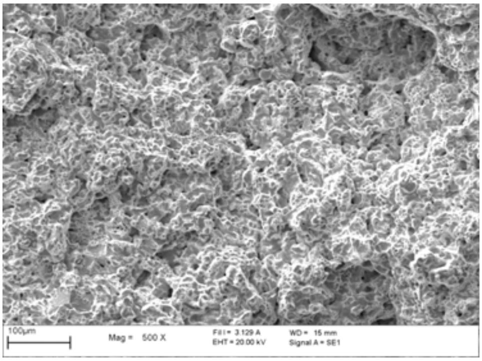

Fig.7. SEM image, system B, 500x.

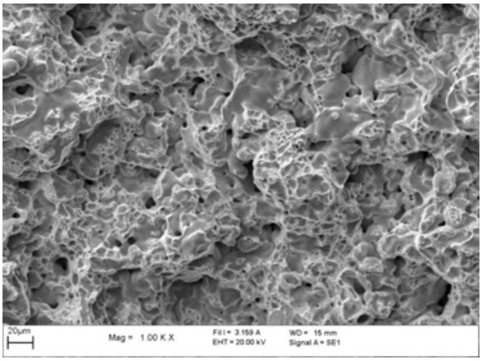

Fig.8. SEM image, system B, 1000x.

The assessment of surfaces related to system B, reported an overall brittle mechanism. The spread of areas formed by dimples is lower with respect to the system A. From the picture related to higher magnification, the differences between this system and the system A were noticeable. The micro-dimples areas were not as wide as the system A, and brittle areas were, for this composition, more numerous and large in dimensions. This effect, is related to the admixing of elemental Nickel powder to the compound, since, as it was noticeable from the assessment of microstructures, the powder added to the mix is acting as a austenitizing agent. The characteristics deduced from the observation of the surfaces, are coherent to the lower resistance obtained in terms of impact energy.

Connections between ballistic results and mechanical properties

From a pure point of view of results obtained from characterization of mechanical properties, the behaviour of the two systems is comparable. Nevertheless, from a point of view of ballistic properties, the two systems show larger differences. The common feature is that, with respect to the ammunition used to carry out the test, no breaks and no fractures have been observed. Considering the characteristics of fracture surfaces, it is possible to switch to a predictive interpretation, able to determine that, since the System B is the more brittle of the two, it would come fail at lower ballistic energy than the System A. The deeper dent can be understood as closer to the conditions needed to start the formation of a cavity, and definitely to the failure of the armored material. It has been demonstrated that the formation of the cavity can be considered as a mechanism for dissipation of energy [11]. That event means not only the removing of material, a detrimental effect for the protection, but also the transition to a different way for the dissipation of energy. Noted that, it is possible to introduce a specific interpretation for the mechanisms used to dissipate the ballistic energy related to P/M materials. The first step can be identified in plastic deformation. In this phase, the energy is dissipated with the deformation of material. The beneficial influence of a ductile structure to that point is noticeable together with good hardness. The second step starts when it is not allowed to reach more plastic deformation. At this moment, a cavity, with projection of splinters, starts to be created, most of the time coupled with cracks and eventually failure of the armour. The point in which this phase starts depends on multiple aspects, as, for example, geometries and thickness of armored equipment. Considering the results from mechanical characterization, it is possible to consider the System B as the more prone to switch to the formation of a cavity, since the subsidence associated to ballistic impact resulted to be higher. A good combination of hardness, ductility and toughness, and a dimple-based, uniform fracture surface, are requested to comply ballistic application. Noted the difference in terms of mechanical properties of the two systems, it is possible to understand, with a predictive approach, the behaviour of materials towards resistance to ballistic impact.

CONCLUSIONS

Towards ballistic performances, both the systems were able to offer the toughness needed with respect to the ammunition used. The results obtained allow setting up a new way for a predictive assessment of ballistic resistance, based on interpretation of mechanical properties and fracture surfaces. The starting point to produce materials suitable for ballistic application must incorporate a good balance of mechanical characteristic, obtained with proper thermal treatment and good structure, with high level of sintering and low amount of porosity. The compositions tested let to underline a detrimental effect related to admixing of powders, in comparison with materials created from pre-alloyed powder. Given the utmost importance to a proper mixing phase, the choice of powders to be use should be carried out minimizing the addition of other powders to the main one, choosing to use pre-alloyed powders and working with best processing conditions.

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