

Ignitable reactive Al-Ni-Me_xO_y composite products by ball milling and ultrasonic powder consolidation

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Abstract



Hybrid, ignitable reactive composites of aluminium with nickel and metal oxides (Fe₂O₃, CuO) were fabricated by low-energy ball milling/mechanical alloying (BMA) and preheated ultrasonic powder consolidation (UPC). In BMA, lamellar particulates were produced and consolidated into pellets by cold-pressing, into sandwich sheets between thin aluminium foils, and loose admixtures with additional Al powders or coatings. In UPC, full-density consolidates of hybrid bimetallic-thermite systems were consolidated at various compositions. The resulting composites are ignitable by low-voltage electric discharge to high-temperature/high heat output self-propagating exothermic reactions (SPER). These were studied by differential scanning calorimetry (DSC) and infrared pyrometry, and the ignition temperature, exotherm enthalpy, adiabatic temperature and SPER front velocity were found to depend on initial composition, processing conditions, product particle/lamella distribution, and thermal impedance of the final material. BMA and UPC are shown to provide fast, robust, affordable and scalable routes for manufacturing of high value-added thermal composite products of aluminium for structural welding, electronic bonding and rapid thermal processing, self-sintering and self-heating materials, and tools for biomedical cauterization.

Keywords: Nickel; thermite; reactive nanoheater; ball milling; ultrasonic powder consolidation.

1. Introduction

Reactive bimetallic and metal-oxide (thermite) nanostructures (nanoheaters) based on aluminium have recently found renewed interest in applications such as microelectronics rapid thermal processing, welding and soldering; microcoating and microjoining; self-sintering powders, self-curing composites and self-heating materials; biomedical assay microchips and cauterization catheters etc [1]. This is owed to their demonstrated electrical or thermal ignitability to react and release highly-localized, instantaneous, precise amounts of heat through self-propagating exothermic reactions (SPER). To achieve desirable SPER performance (ignition level, adiabatic temperature, front velocity etc), the form and dimension distribution of such hybrid structures needs to be engineered via proper material and process engineering.

Recent developments in facile synthesis of ignitable, exothermically reactive nanostructures, has introduced the ultrasonic powder consolidation (UPC) process [3]. Reactive composites of compositions 2Al-Fe₂O₃-x(Al-Ni) and 2Al-3CuO-x(Al-Ni) (x = 1 - 4) were fabricated from nano-thick Al and Ni flakes and Fe₂O₃ and CuO nanoparticles by UPC. Application of in-plane ultrasonic vibration for 1 s at 573 K under a uniaxial pressure of 100 MPa produced full-density consolidates. In addition, bimetallic Al-Ni nanostructures [4], have renewed interest in the ball milling / mechanical alloying (BMA) process. Actively-cooled high-energy BMA has been attractive for continuous production, while low-energy BMA has been better suited to batch fabrication under experimentally controllable and observable conditions in the laboratory [5].

Both solid-state processes are presented in this paper for material particles including metal and oxide powders. The resulting consolidate structures consisting of globular and/or lamellar formations from the micro- to nano-scale are also studied through metallurgical and thermal analysis, assessing their SPER characteristics.

2. Ultrasonic power consolidation

2.1. Material preparation

For the UPC process, thermal plasma-synthesized Fe_2O_3 and CuO nanoparticles (20-40 nm and 30-50 nm in size, respectively) all purchased from Alfa Aesar and Al and Ni nanoflakes with sub-micron thicknesses (100-300 nm) produced by a proprietary ball-milling technique at Fukuda Metal Foil & Powder Co., Ltd. were used as the raw materials. Figure 1 shows SEM pictures of the as-received particles. The Fe_2O_3 and CuO nanoparticles were agglomerated. The Al and Ni flakes came coated with stearic acid to prevent pyrophoric reactions during commercial shipping and storage. Therefore, the flakes were first rinsed in agitated ethanol for 2 minutes and dried in air. Removing the acid did not cause pyrophoric oxidation as they were still protected by their pre-existing surface oxide.

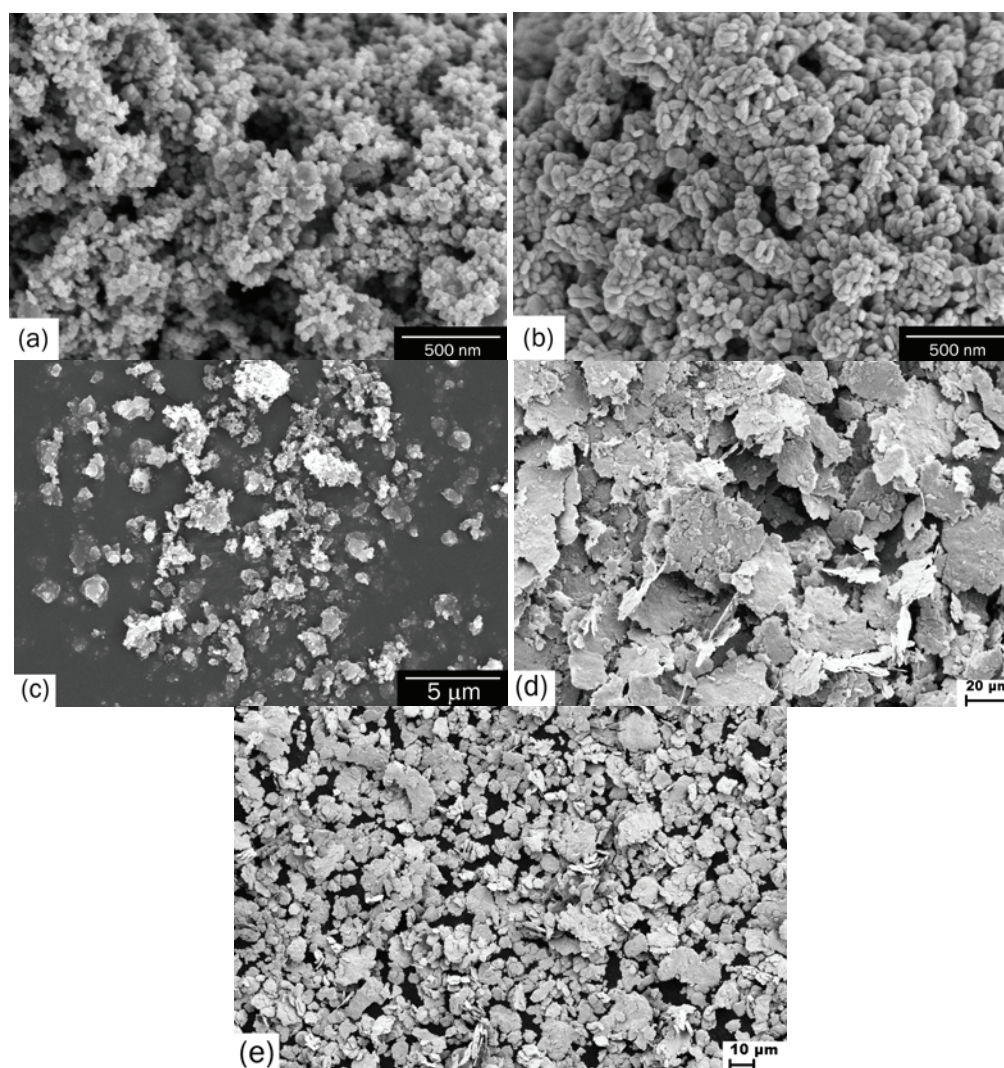


Figure 1. SEM pictures of as-received (a) Fe_2O_3 nanoparticles, (b) CuO nanoparticles, (c) Al_2O_3 particles, (d) Al flakes and (e) Ni flakes.

Similar bimetallic Al-Ni (1:3) lamellar micro/nano-structures were obtained with low-energy ball milling. Near optimum SPER behavior was obtained after 4 h of continuous milling with nanoscale lamellae and some remaining relatively thick Ni layers. BMA beyond the optimum point increases the solid-state diffusion of Al into Ni-rich solid solutions that negatively impacts the heat output and the thermal wave velocity. Upon proper activation, reactivity of such multilayer structures critically depends on the size distribution of the bilayer dimension, i.e. the thickness of its elementary components: Thinner bilayers between smaller particles, because of their higher surface/volume ratio, seem to require less specific activation energy and upon ignition tend to react at lower temperatures and faster rates, as the thermal conduction / material diffusion – limited reaction process needs to penetrate smaller depths; While larger components tend to react at higher stimuli with slower kinetics. Therefore, in a hybrid self-similar structure spanning a range of bilayer dimensions, uniform ignition activates smaller particles first, which upon reaction produce the necessary thermal activation (i.e. temperature raise) for larger particles to react and so on. The high thermal conductivity and low eutectic temperature of aluminium appears to play an enabling role towards such a cascaded SPER with a moving front.

5. References

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