Dual phase magnetic functionalization of multicomponent alloys

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This work focuses on the collaborative behavior of strong ferromagnetic FeCr nanoparticles embedded in a AlNiCo weak magnetic matrix.

"The whole is greater than the sum of the parts." The quote reflects on the mathematical observation, of the original phrase attributed to Ἀριστοτέλης, that, in a broader and more modern Systems Engineering language, can be rephrased as "The System is something beside, and not the same as, its elements." [1].

Illustrations of both readings can be found in modern applied sciences. For example, the intensity resulting from the interference of two beams of equal intensity can go from none to up to four times the brightness of the individual beam. Another example: ferromagnetic Heusler alloys are made of non-ferromagnetic elements such as Manganese, Nickel and Tin [2].

In this contribution, we investigate the increased magnetization of $NiCoFeCrAl_x$ multicomponent alloy by means of its $FeCr$-$NiCoAl_x$ dual phase functionalization.

For this study, bulk samples of stoichiometric composition $Ni_{0.5}CoFeCr_{0.5}$-Al_x (named Al0.0, Al1.0 and Al1.5 for $x = 0.0$, 1.0 and 1.5, respectively) were arc-melted at least three times before being heat-treated at 1423 K for 10 h in Argon atmosphere [3, 4].

Figure 1 shows the magnetization vs. temperature measurements for applied fields of 25 mT (a) and 1.0 T (b). Notice the evolution from a single characteristic Curie Temperature (T_C) for the Al0.0 sample, to a double-magnetic transition with Al addition. The split of the magnetic transition is found to be concomitant to the transition from a single FCC (Al0.0) transition into a dual BCC/B2 phase (Al1.0 and Al1.5) [3]. Also notice the formation and segregation of FeCr-nanoparticles (NPs) within an AlNiCo-rich matrix with Al addition (Figure 2a, 2b and 2c). The two distinctive values of T_C for the fully segregated Al1.0 and Al1.5 samples correspond to $T_C^{FeCr} > 850$ K and $T_C^{AlNiCo} < 700$ K, respectively [3].

FeCr-NPs were found to make the greatest contribution to the total magnetisation in the Al1.0 and Al1.5 samples. However, the jump in magnetisation occurring at T_C^{AlNiCo} is approx. 5 times larger than the magnetisation change observed at T_C^{FeCr}. (The result can seem counterintuitive at first sight.) In turn, the saturation magnetisation (M_s) at 300 K and 1.0 T is 100 Am^{2}kg^{-1} and 70 Am^{2}kg^{-1} for samples Al1.0 and Al1.5, respectively, which is higher than the 62 Am^{2}kg^{-1} measured for sample Al0.0 at its saturation ($T = 50$ K) and only 20 Am^{2}kg^{-1} at 300 K (Figure 1).
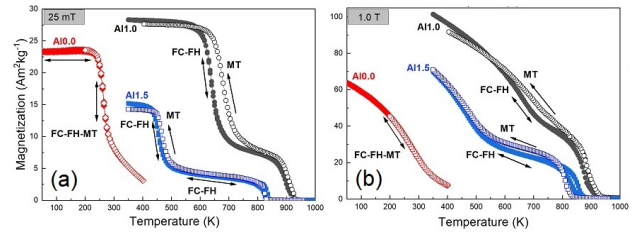

Figure 1: Shows the FC-FH path of direct M(T) measurements curves (solid symbols) and the indirect magnetization dependence on temperature (MT) curve obtained from isothermal measurements of the virgin loop in a decreasing temperature path (open symbols) for samples Al0.0 (red), Al1.0 (black) and Al1.5 (blue) at applied fields of 25 mT (a), and 1.0 T (b).

Thus, with the addition of the paramagnetic Al, the magnetic properties of the Al0.0 sample are considerably enhanced, enlarging the FM region (i.e. shifting T_C for more than 170 K towards higher temperatures) and increasing M_s by 61% and 16% for Al1.0 and Al1.5, respectively.
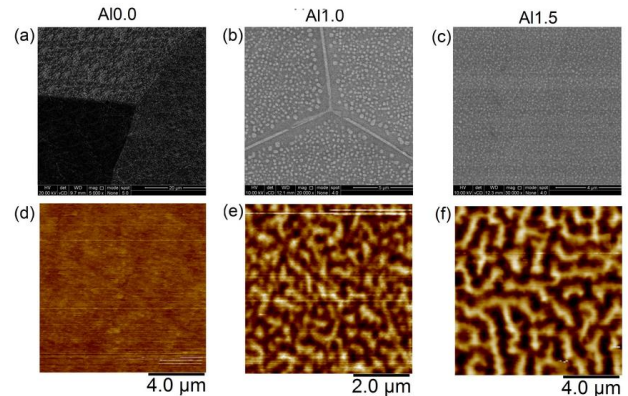

Figure 2: SEM (a, b, and c) and MFM (d, e, and f) image of Al0.0 (a and d), Al1.0 (b and e), and AL1.5 (c and f) at different magnification.

In order to explain the findings, a phenomenological approach was used where the collaborative interaction amongst NPs was taken into account. The following conclusions were reached:

1. FM-NPs of FeCr rich phase forms at T_C^{FeCr}.

2. As the temperature decreases, with the decrease of the thermal energy in the region $LTT < T < HTT$, dipolar interaction among NPs is favoured

for particles of larger size (i.e. Al1.0 sample). Unfavoured NPs' interaction in the Al1.5 sample show an SPM-like collective behaviour where NPs are weakly linked to their neighbours.

3. As the sample reaches $T_\mathrm{C}^{\mathrm{AlNiCo}}$, the matrix becomes FM and provides the conditions to form the exchange-bridge that will enhance the FM-NPs interaction. As a consequence, already strong linked NPs of the Al1.0 sample increase the FM-like short-range interactions, which, in turn, increases the long-term dipolar repulsion that forms a highly fragmented AFM-like domain structure to minimise the energy of the system (Figure 2e). On the other hand, the smaller NPs of the Al1.5 sample are weakly ferromagnetically aligned, which, in turn, decreases the long-range dipolar repulsion interactions and allows for a wider stripes labyrinth domain structure to form (Figure 2f).

Notes

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References

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