Copper permalloys for fluxgate magnetometer sensors

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SUMMARY

Fluxgate magnetometers are commonly used to provide high-fidelity vector magnetic field measurements. The magnetic noise of the measurement is typically dominated by that intrinsic to a ferromagnetic core used to modulate (gate) the local field as part of the fluxgate sensing mechanism. A polycrystalline molybdenum-nickel-iron alloy (6.0–81.3 Mo Permalloy) has been used in fluxgates since the 1970s for its low magnetic noise. Guided by previous investigations of high permeability copper-nickel-iron alloys, we investigate alternative materials for fluxgate sensing by examining the magnetic properties and fluxgate performance of that permalloy regime in the range 28–45 % Cu by weight. Optimizing the alloy constituents within this regime enables us to create fluxgate cores with both lower noise and lower power consumption than equivalent cores based on the traditional molybdenum alloy. Racetrack geometry cores using six layers of ~30 mm long foil washers consistently yield magnetic noise around 4–5 pT/√Hz at 1 Hz and 6–7 pT/√Hz at 0.1 Hz meeting the 2012 1-second INTERMAGNET standard of less than 10 pT/√Hz noise at 0.1 Hz.

Keywords: fluxgate, magnetometer, copper-permalloy,

INTRODUCTION

In December 2007 one of us (Narod) rediscovered a paper by von Auwers and Neumann (1935), titled in English “On Iron- Nickel-Copper Alloys of High Initial Permeability,” and this eventually set into motion our examination of copper permalloys as potentially useful materials for fluxgate magnetometer sensors. Specifically, we are interested in copper permalloy’s potential to simultaneously provide low magnetic noise and low power consumption in a fluxgate sensing application. With the assistance of colleagues at Zentralanstalt für Meteorologie und Geodynamik [ZAMG, now Geosphere Austria] we had located a loose paper copy in a box of collected papers, situated in the library of the Austrian Academy of Sciences in Vienna, a collection which conveniently for us had been catalogued by their librarians. This paper was last cited in 1961 (Puzei, 1961), and had disappeared from living memory. A single citation of it in Bozorth (1951) had caused us to spend several years searching for it. The collection of copper permalloy data included in von Auwers and Neumann (1935), extraordinary in both quantity and quality, are reproduced in translation:

https://egusphere.copernicus.org/preprints/2023/egusphere-2023-2191/

THE CASE FOR COPPER PERMALLOYS

Miles et al., (2022) presented along with 6%Mo permalloy our first trial of a copper permalloy. This alloy consisted of 28% copper, 62% nickel and balance iron, which we designate 28Cu62Ni. The case for 28Cu62Ni went as follows:
We knew that 6%Mo permalloy has several properties that are thought advantageous for fluxgate sensor materials. These are 1) minimum magnetocrystalline anisotropy, 2) minimum bulk magnetoelastic anisotropy, 3) minimum saturation magnetization of all such materials satisfying 1) and 2), and 4) a requirement for slow cooling during heat treatment, to minimize residual stress (Pfeifer, 1966; English and Chin, 1967; Pfeifer and Boll, 1969). These papers all placed the zero-crossings satisfying 1) and 2) over a range of compositions including 4-6% molybdenum. But from their Figures 6%Mo uniquely also satisfied both 3) and 4), and these papers’ Figures ultimately drove the choice to use 6%Mo in a new generation of fluxgate magnetometers.

Our first trial with a copper fluxgate sensor made from 28Cu62Ni (Miles et al., 2022) produced performance results comparable to a nominally identical sensor made from 6%Mo permalloy, and for some parameters such as power consumption the 28Cu62Ni alloy sensor outperformed. The success of our initial copper alloy trial encouraged us to expand our investigations of copper permalloys, seeking more resolution in composition and extending our fluxgate sensor builds to alloys with much higher copper contents. It is well known that lower $\boldsymbol{B}_{\text{sat}}$ leads to improved noise performance.

The choices for our alloy compositions were guided by von Auwers and Neumann (1935). For the copper contents we selected the range 28-45%Cu. For our minimum copper-content alloys we chose 28%Cu with about 60%Ni. This coincided with the maximum initial permeability measured by von Auwers and Neumann (1935). This collection included 52 specimens, with the composition range plotted in Fig. 1.

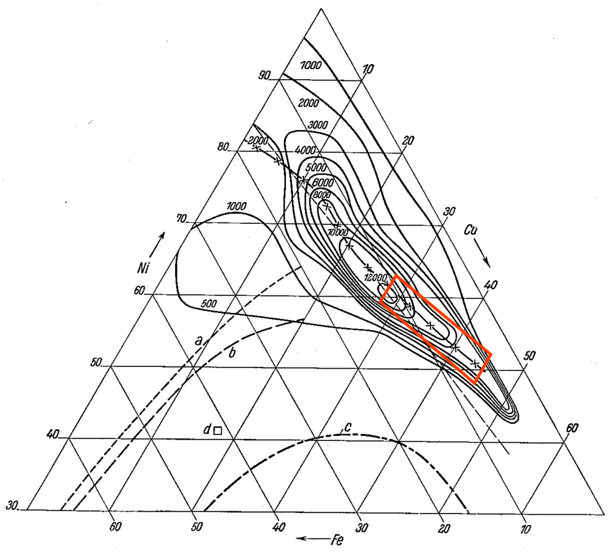

Figure 1. The range of copper-permalloy compositions in our study, outlined in red and superimposed on von Auwers and Neumann (1935) Fig. 8.

DISCUSSION

We measured DC resistivity, saturation induction, initial permeability, DC coercivity on fifty of our alloy specimens. Four of our specimens were further tested for Curie temperatures and were built into racetrack fluxgate sensors for further performance testing. Noise and power consumption results are presented in Fig. 2.

All our magnetic properties data with discussions, and a discussion of a century of history of copper permalloys, are now published as a research paper:

https://egusphere.copernicus.org/preprints/2023/egusphere-2023-2191/

The reader is directed to this publication.

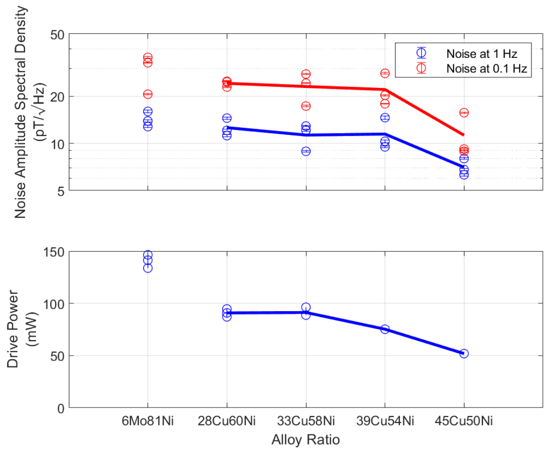

Figure 2. Fluxgate noise PSD and power consumption for five alloys.

We expected that as we increased copper content both power consumption and noise PSD would be reduced, the former from the lower field strength needed for saturation and the latter due to the well-known relation between saturation and noise PSD. These relations were both confirmed. What we did not know in advance was how hypothetical poorer magnetic anisotropy levels might impact the measured magnetic properties and noise levels. Narod (2014) predicted that such impacts should vary only slowly with anisotropy and our data confirm that. By far the biggest impact magnetic properties have on sensor noise performance is that of saturation induction.

CONCLUSION

Our investigation of the 28-45% copper permalloy regime's magnetic properties has led us to alloys which have yielded fluxgate sensors with noise PSD and power consumption improvements over those of the legacy 6Mo81.3Ni permalloy composition. Racetrack sensors of our lowest noise and power alloy, 45Cu50Ni, have noise PSD levels well below 10pT/√Hz at both 1.0Hz and 0.10Hz, easily satisfying the 1-second INTERMAGNET requirement (Turbitt, 2014).

Our first alloy selected for further sensor testing, 43Cu52Ni, shares its 100C T_c with our lowest noise alloy, 45Cu50Ni, but has much higher initial permeability. Many uses for low noise magnetic sensors require long durations of data collection, and sensor stability, over both time and temperature is an issue. Our future investigations must address these properties.

Our present results have relied heavily on the existence of the data presented by von Auwers and Neumann (1935), but no such comprehensive examination of molybdenum permalloys was ever undertaken. There may yet be room for improvement of molybdenum permalloys in fluxgate sensors, with molybdenum content higher than that of the legacy 6% materials. In our future work we plan to investigate these alloys.

The performance of these new alloys is expected to enable further miniaturization of the fluxgate sensor while preserving geophysically useful magnetic sensing performance.

ACKNOWLEDGMENTS

That authors wish to thank Christian Hansen, Andrew Schmitt, Matt Miller, and Toby Tompkins for their work manufacturing and machining the permalloy samples, Tino Smith for his work assembling the fluxgate cores, and John Bennest for his work characterising $\boldsymbol{B/H}$ loops. This research has been supported by the National Aeronautics and Space Administration (grants no. 80NSSC19K0491 and 80GSFC18C0008).

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