EFRE 2020

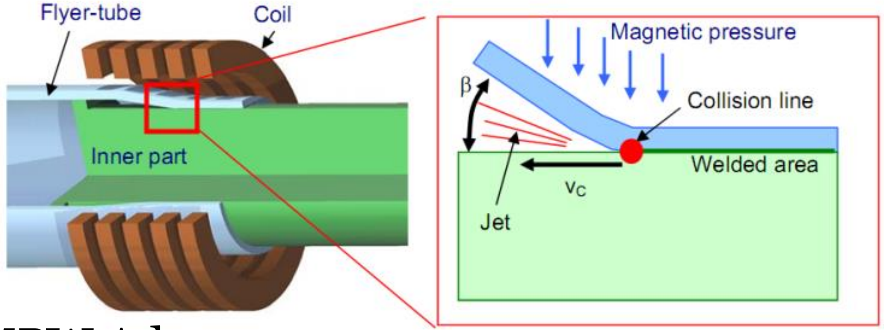
MAKING GRADIENT SURFACE CONDUCTIVITY OF STEEL AND STUDY THE EFFECTS UNDER HIGH PULSED MAGNETIC FIELDS

Evgeny Yu. Zaytsev, Alexey V. Spirin, Sergey N. Paranin, Vasiliy I. Krutikov, Vladimir R. Khrustov, Sergey V. Zayats

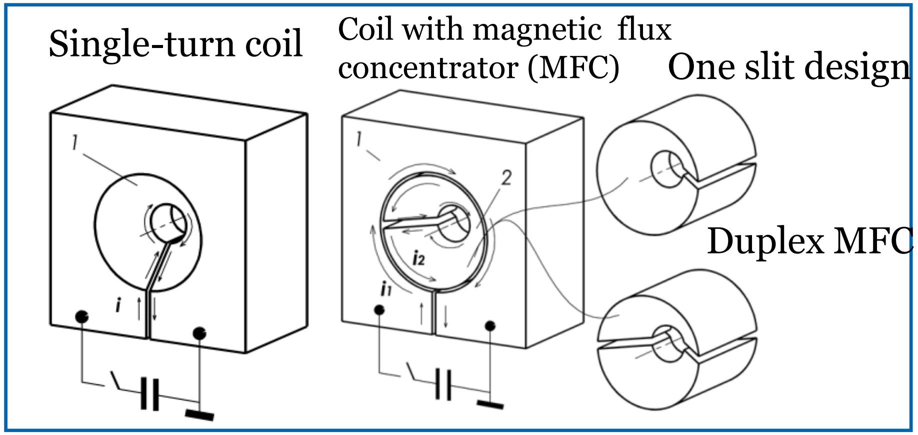
Institute of Electrophysics UB of RAS, Yekaterinburg, Russia

Introduction

Magnetic Pulse Welding (MPW) Process Scheme



Mostly Used Cylindrical Tool Coil Designs



<u>MPW Advantages:</u>

- Solid-phase metallurgical joining,
- Ability to join dissimilar materials,
- Joining of hard-to-weld materials, etc.

Problem:

Coil low durability through failure

Be-bronze coil

Steel MFC

Steel coil

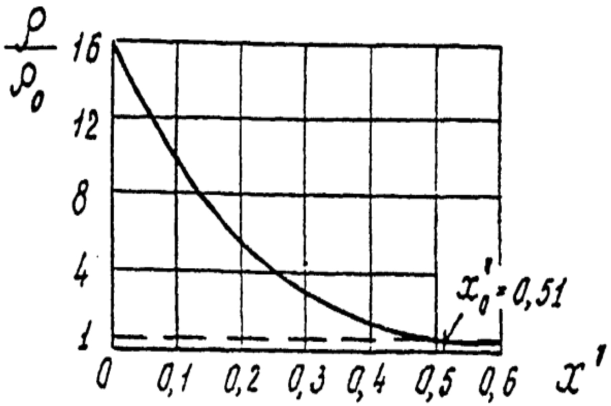
Reason:

Intensive thermo-mechanical stresses at inductor surface because of: (1) high "magnetic pressure", (2) surface overheating. Magnetic pressure is up to 1 GPa, T ~ 600-800°C.

Conductor Surface Heating Reduction

THEORETICAL ANALYSIS

Example of Resistivity Steadily Decreasing with Depth [1]



$$B_e(t) = B_o \cdot exp(t/t_0)$$

$$\Delta q(x,t) = \frac{B_e^{\,2}(t)}{\mu_o} \cdot \frac{1}{\left[\sqrt{ln(\rho_1/\rho_0)} + 1\right]^2}$$

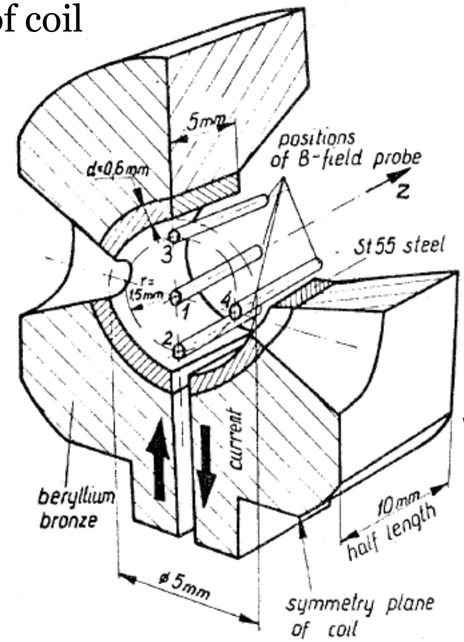
χ

Exam.: $\rho_1/\rho_o = 5$ → **$\chi = 0.194$**

PRACTICE

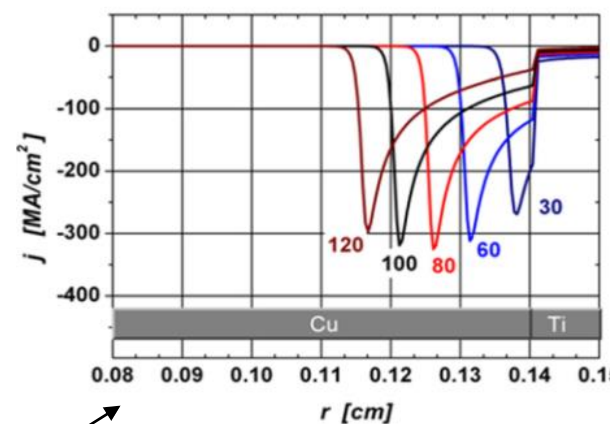
Double-Layered Coil [2]
"Be-bronze (bulk) / Steel (channel surface)"

Axonometric view-section of coil



Double-Layered Wireway [3]
"Cu (bulk) / Ti (surface)"

Predicted current density distribution along radius



LAYERED STRUCTURES

BUT

DIFFUSED STRUCTURE

[1] Shneerson G.A. 1992 Technical Physics Letters 18 (6) 18

[2] Farinski A, et al. 1981 IEEE Trans. on Magnetics 17(5) 1935

[3] Chaikovsky S.A., et al. 2014 Physics of Plasmas 21 042706

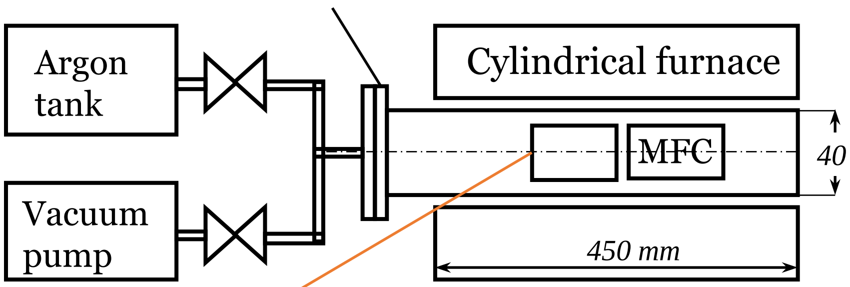
Aim

Development of new materials and approaches to enhance the performance of magnetic pulse tools

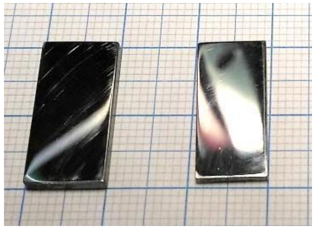
Objectives

- Study conditions for obtaining diffusive layer structure and its properties;
- Measure depth distribution of resistance;
- Apply powder technology to create a layered structure;
- Study the properties of a powder samples;
- Test the samples under HMF generation.

Facility for Steel Pack Chromizing

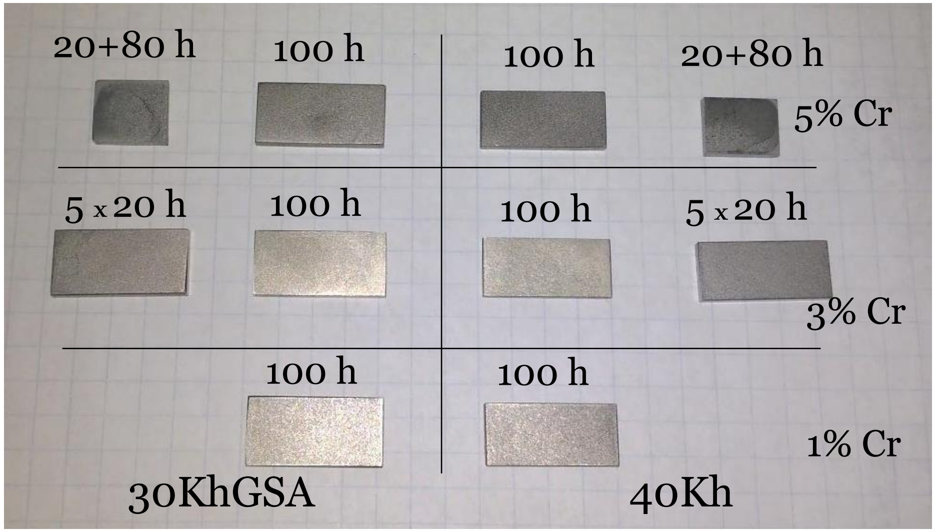


Quartz sleeve with plates



Plates before Chromizing

Chromized specimens



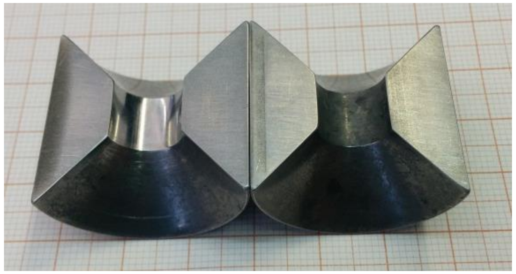
Chromizing conditions

	Pack composition (wt. %) (Al_2O_3 – balance)	Pack amount (g)	Total surface of samples (cm^2)	Cr-load ($mg \cdot cm^{-2}$)	Environment	T_H / T_L (°C)	Duration (h)
I:	0.5% NH_4Cl – 5% Cr	20 ± 0.5	20	50	Ar @ 1.15±0.05 bar	1000 ± 10 / RT	20 / 50 / 100 / 20+80 (cycl.)[2]
II:	0.3% NH_4Cl – 3% Cr	20 ± 0.5	20	30		1000 ± 10 / RT	100 / 20 h×5 (cycl.)[2]
III:	0.1% NH_4Cl – 1% Cr	20 ± 0.5	20	10		1000 ± 10 / RT	100
IV:	0.2% NH_4Cl – 2% Cr	23 ± 0.5	23	20		1000 ± 10 / 500	10 h×15 (cycl.)[2]

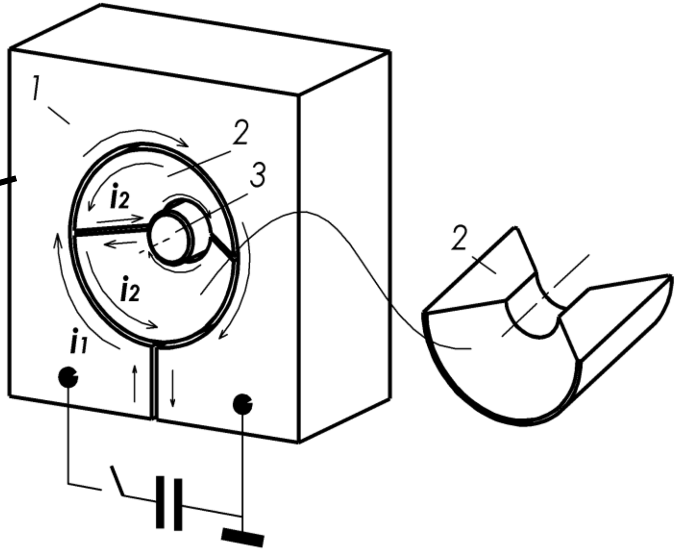
Testing under HMF conditions

Chromizing

Quenching and cutting into two symmetrical pieces



Samples of MFCs were treated by chromizing at conditions:
I: 17% Cr-pack, 1000°C/20 h; **II**: 5% Cr-pack, 1000°C/100 h

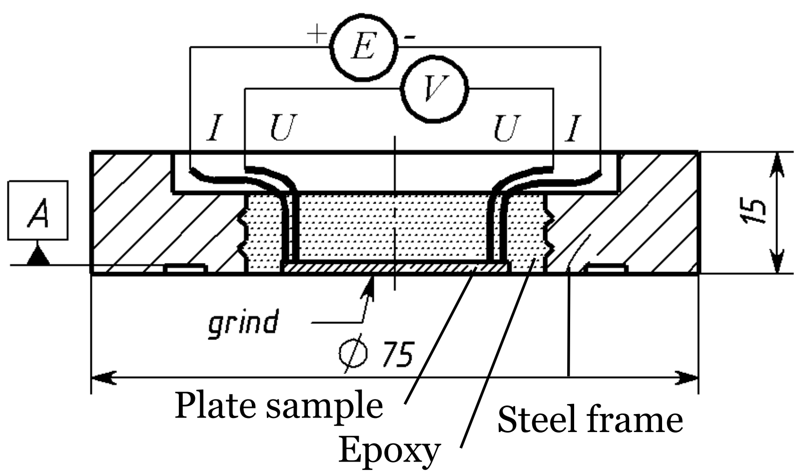


Capacitor Storage: C = 435 μF, U_{max} = 25 kV,
Lo = 60 nH, Ro=15 mOhm

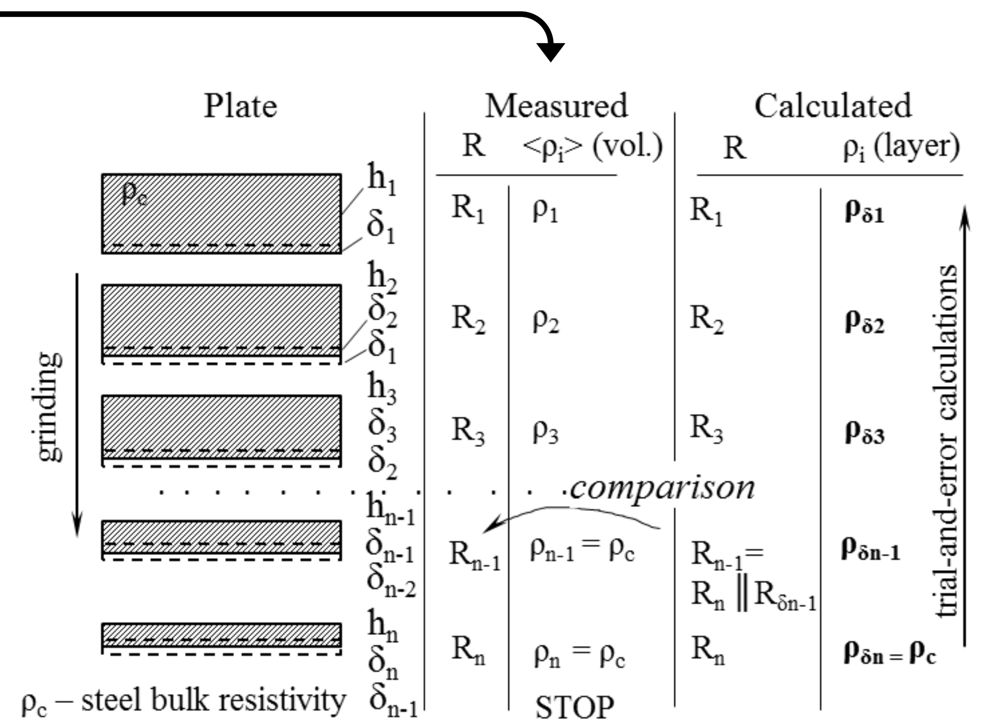
Generating pulse:
B = 50 T; T/2 = 15 us

Resistivity distribution measurements

Thin layer (~20 um) was ground off the sample, then the measurement was carried out. It was repeated until the resistivity of the plate stops changing. Resistivity of removed layers could be calculated by suggested algorithm:



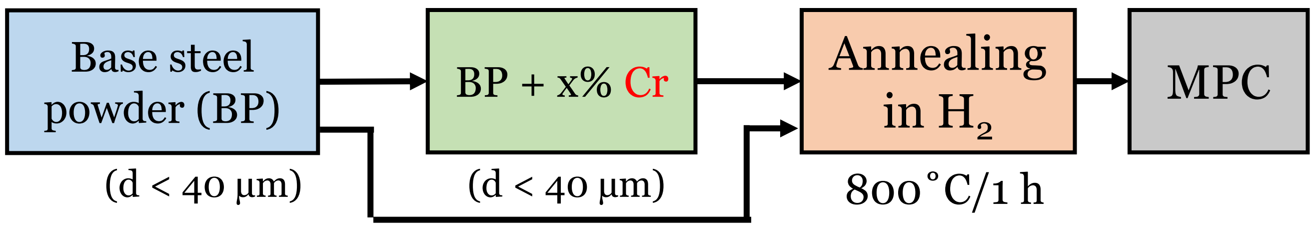
Schematic diagram of a 4-probe DC method



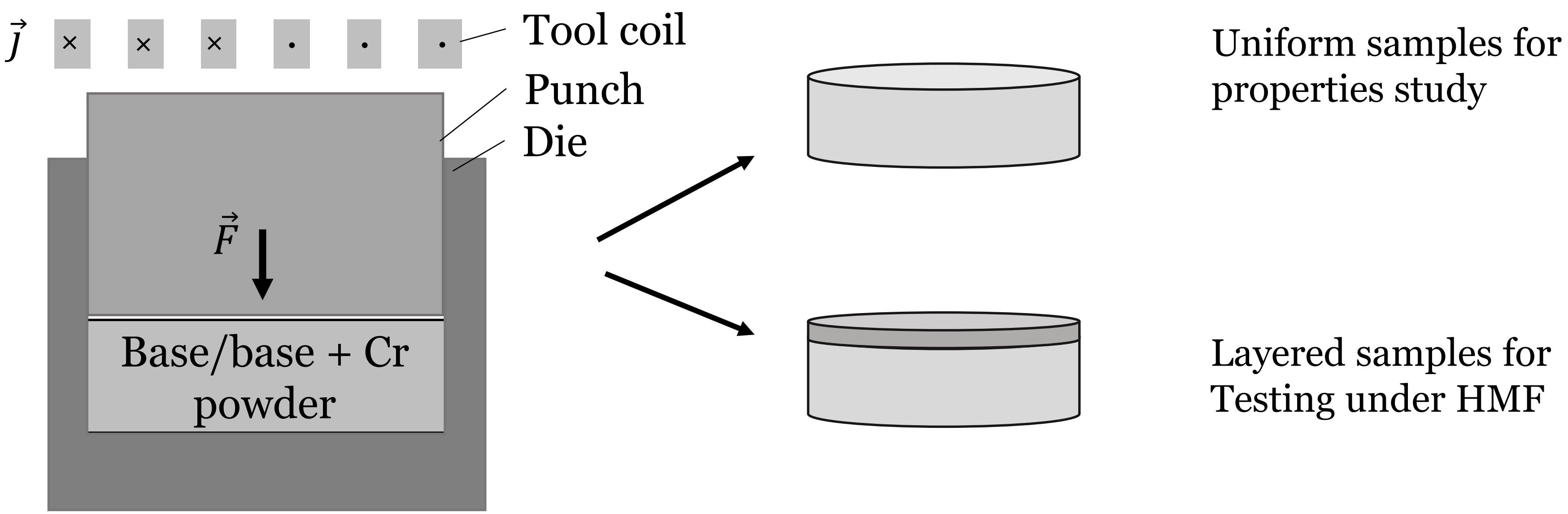
Powder approach to create a layered structure

Advantages:
– Ability to make a resistive layer of different thickness,
– Ability to vary the resistive layer properties (different amount and size of additive),
– Suitable for additive technologies, *etc*.

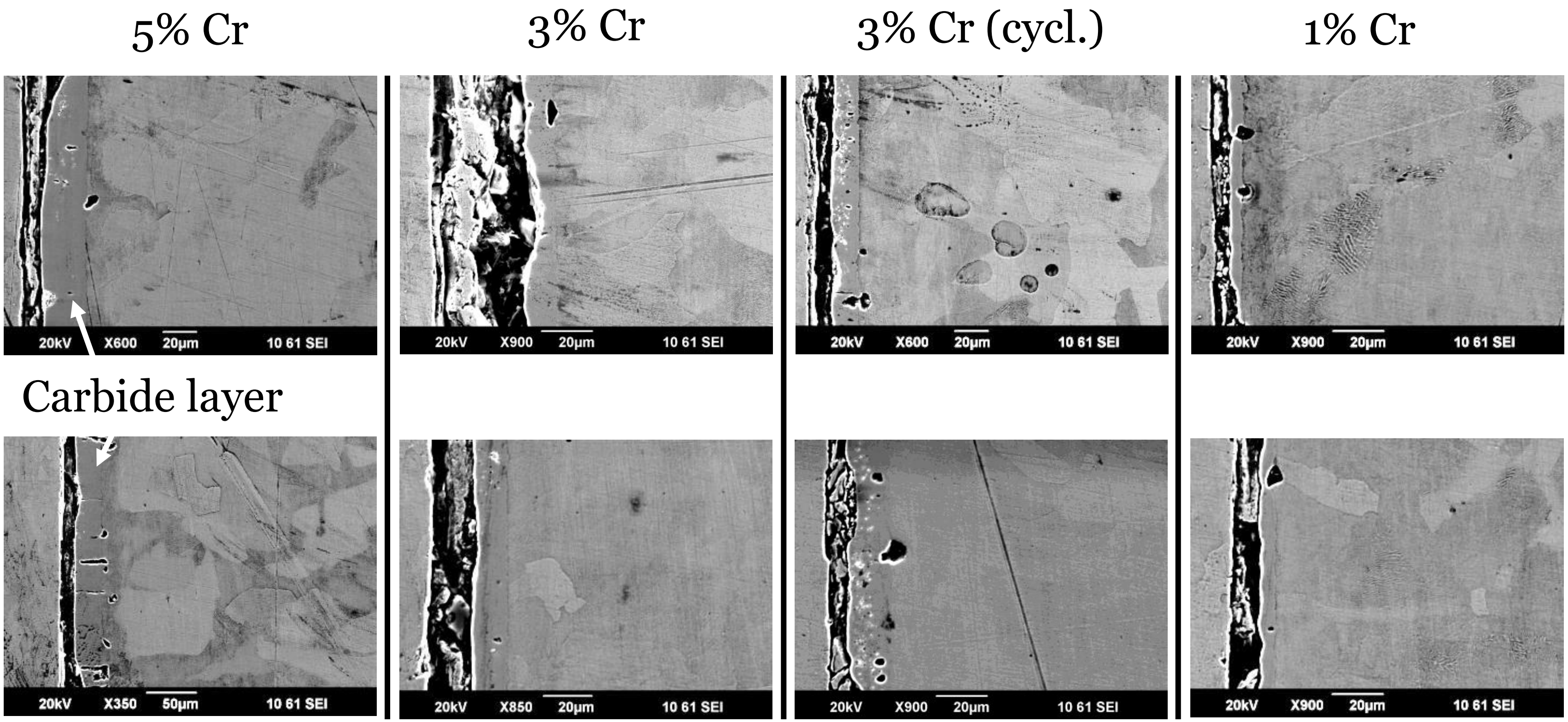
Procedure:



MPC (schematic diagram)

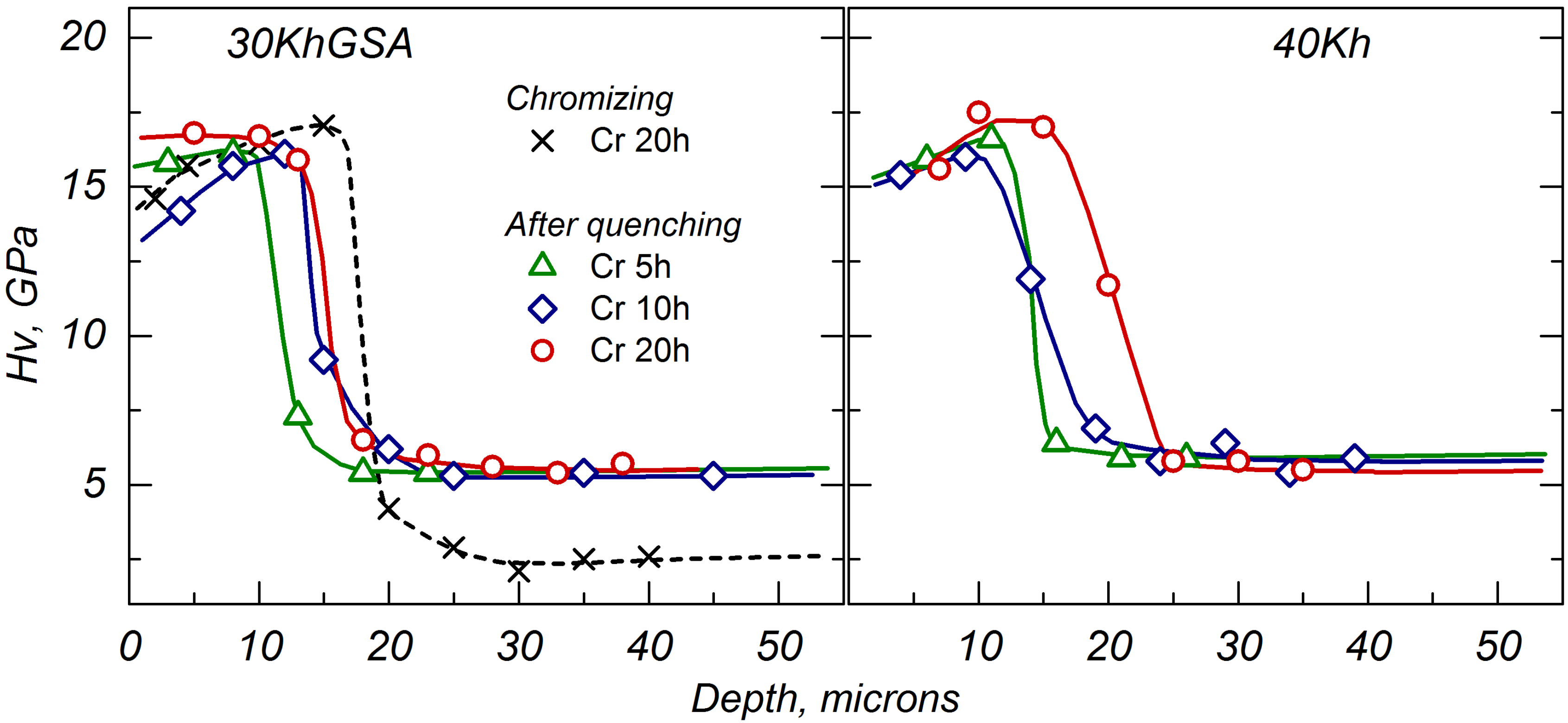


Plates Chromizing results



View of 30KhGSA (top) and 40Kh (bottom) steel plates cross sections in SEM (JEOL JSM 6390LV) after chromizing at 1000°C/100 h using different Cr-packs

Modified Layer Mechanical Properties

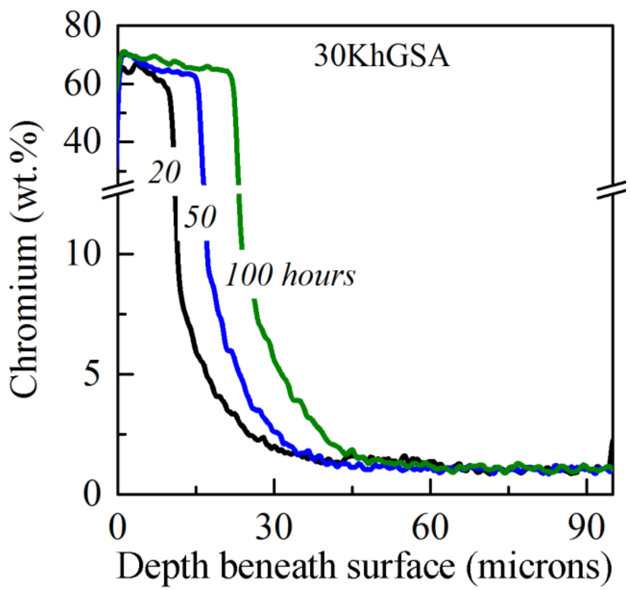


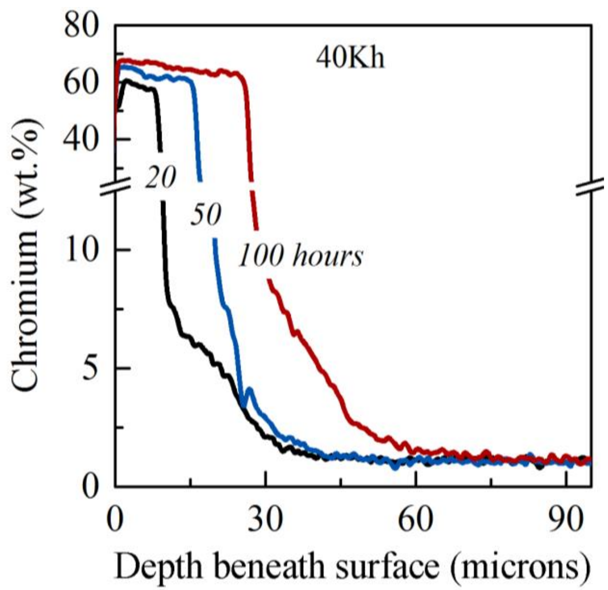
Hv profiles measured on cross-sectioned thick plates after chromizing at 1000°C (5, 10, and 20 h) and subsequent quenching

Properties of Diffuse Coating Layers

Effect of process duration (5% Cr pack)

Coating properties:
- *Hv* microhardness ~17 GPa;
- Mainly consists of chromium-based carbides (XRD);
- Poor continuity and nonuniform thickness.



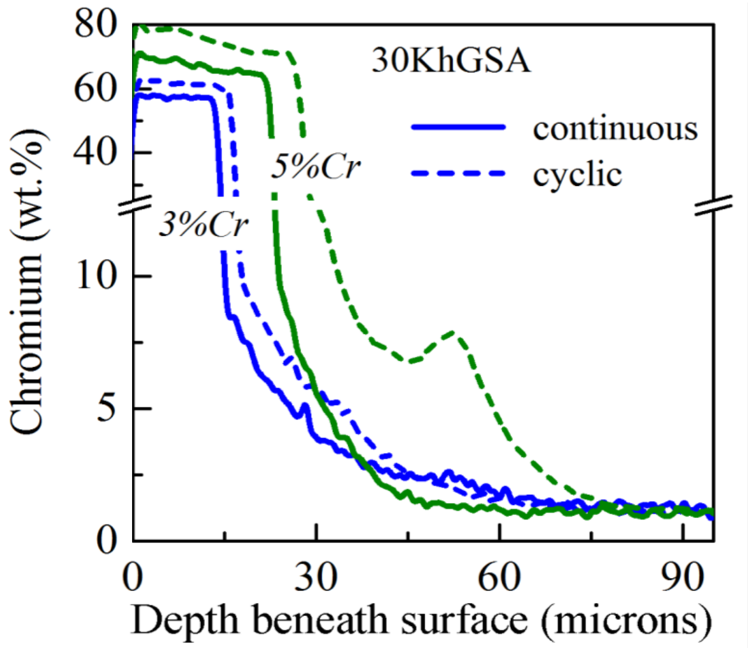


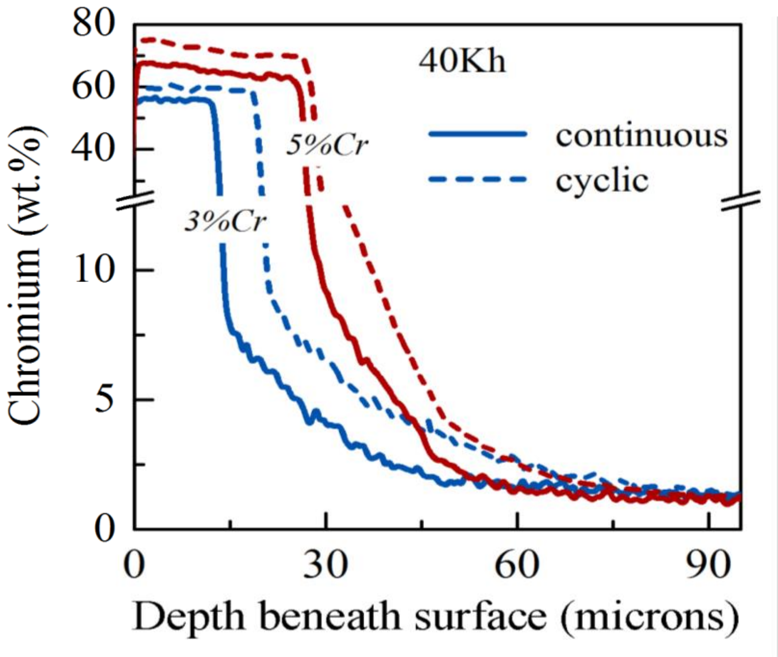
EDX (X-Max (Oxford Instruments) traces for chromium taken across the surface layers

Properties of Diffuse Coating Layers

Effect of pack-type and temperature cycling

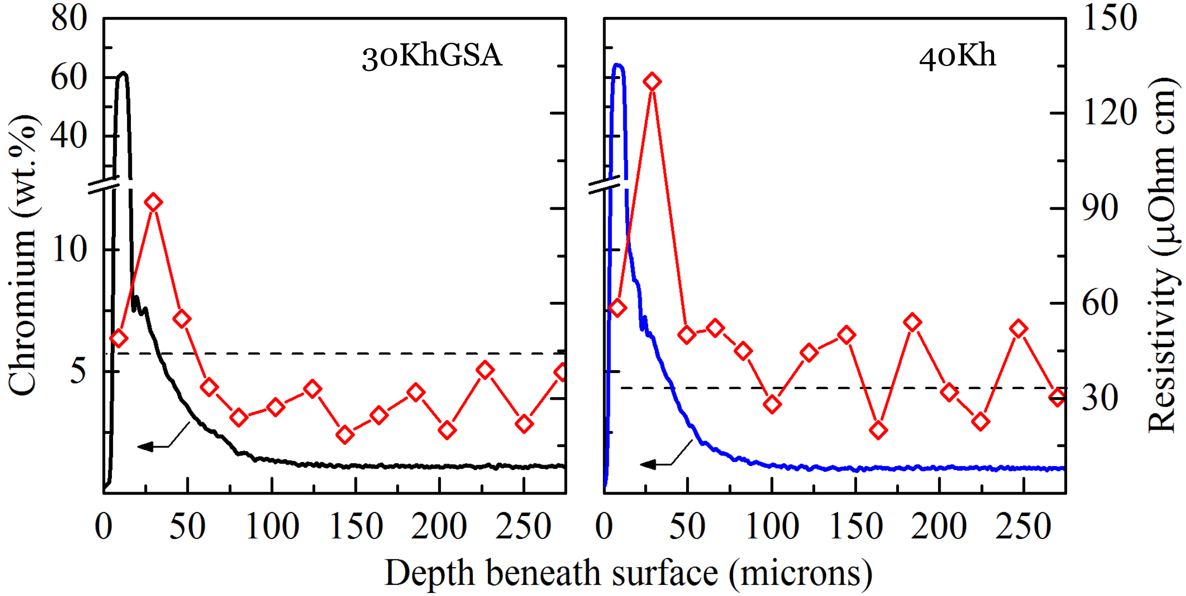
Temperature cycling and increasing chrome load leads to getting **thicker** modified layer





Chromium profiles of as-chromized 40Kh and 30KhGSA plates depending of pack type and thermal regime.

Resistivity distribution measurement results



Samples chromized under:
2% Cr pack,
150 h in total (cycl.)

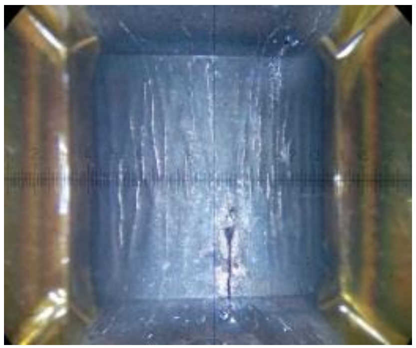
Diffuse layer thickness: 0.1 mm

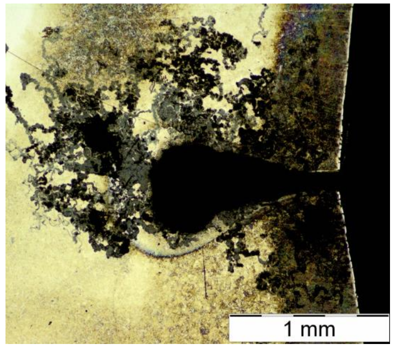
Increase of resistivity in the near-surface region is occurred by a factor of 2–3 for both steel grades.

The results on MFCs testing under HMF

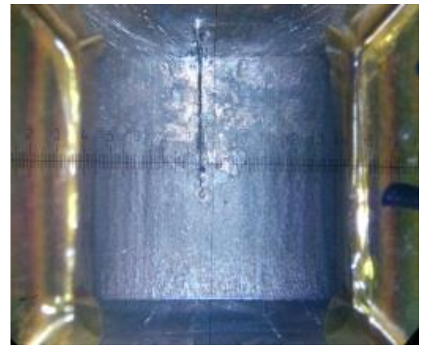
17% Cr - pack

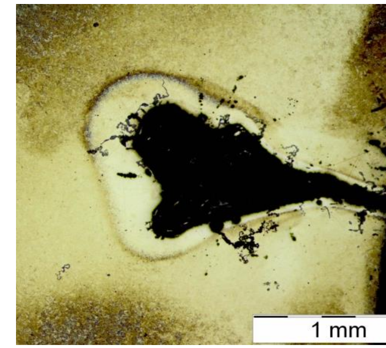
With carbide layer





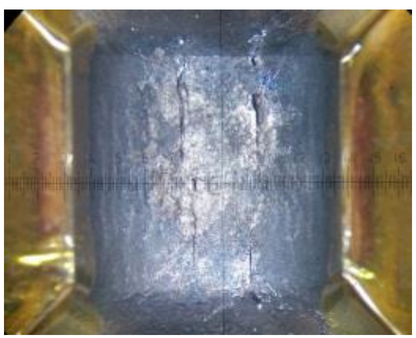
Without carbide layer

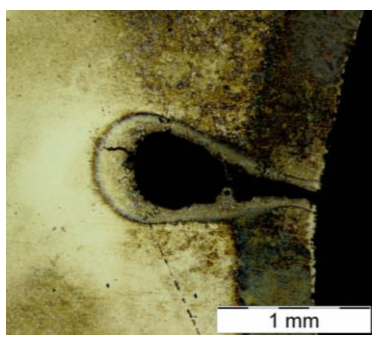




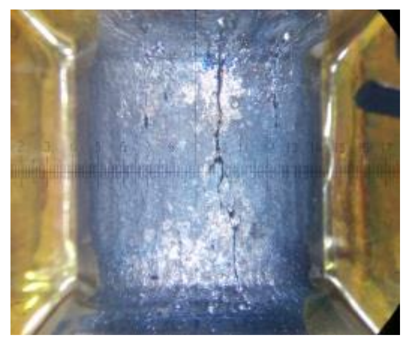
5% Cr – pack

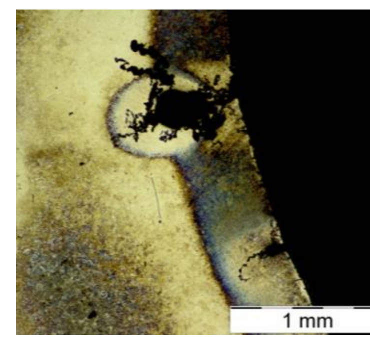
With carbide layer





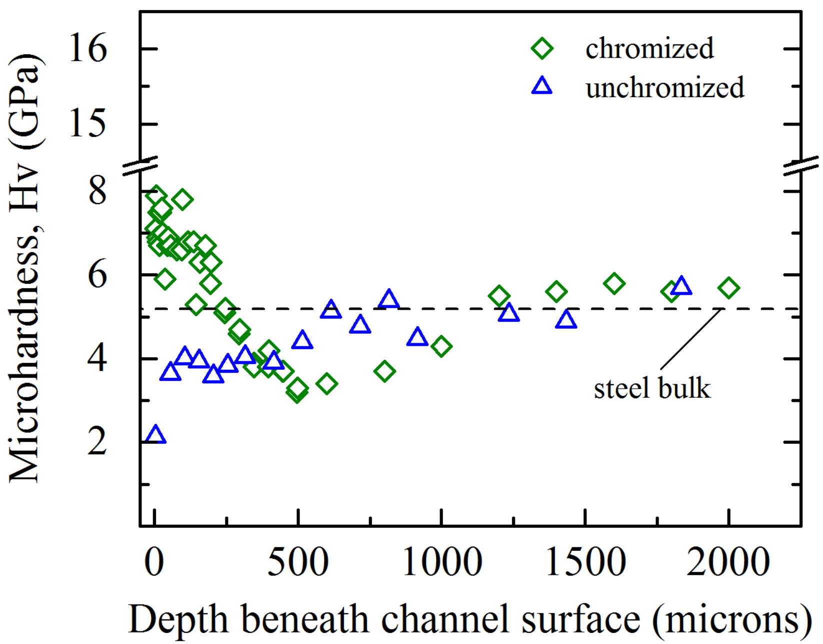
Without carbide layer





View and microstructural characteristics of the working channel of MFCs after the testing under HMF of 50 T peak field (31 pulses)

The results on MFCs testing under HMF



Hv microhardness for 30KhGSA MFCs of two types after the testing under HMF generation

SUMMARY

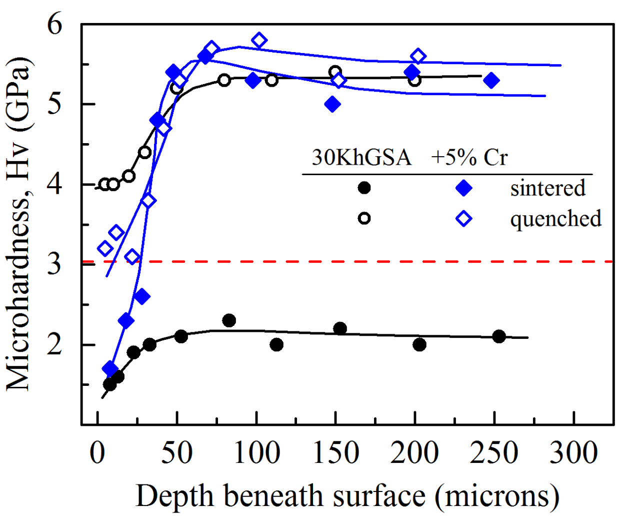
The **relatively small thickness** of the modified layer which is obtained during long-term high-temperature chromizing (100 um / 150 h) and the instability of the structural characteristics of steel at great depths due to carbon migration under such treatment conditions make this approach **unsuitable** for the described steel application.

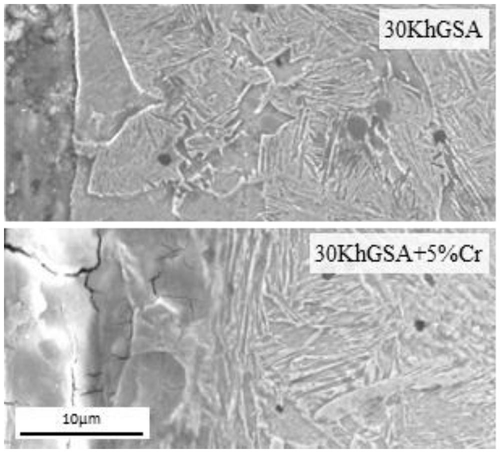
Powder approach and obtained results

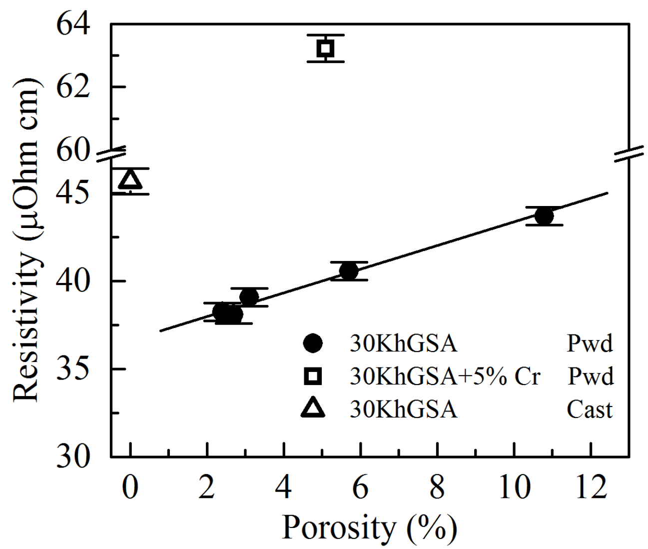
Mechanical, microstructural, and electrical properties of the samples made of 30KhGSA based powders.

Single-layer samples made of different powders was studied in present work.

- Relative density up to 99% was achieved under vacuum sintering at 1200°C for holding time 1.5 to 6 h;
- Porosity influence: at the same composition, the resistivity increases by 35%, from 38 to 44 μOhm·cm, with an increase in porosity from 2 to 11%;
- Cr addition influence: addition of 5% Cr to base powder leads to an increase in resistivity of base material by ~1.54 times.







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Conclusions

- The surfaces of steels 30KhGSA and 40Kh were modified by chromium-plating. Effect of chromium load, temperature cycling, and process duration on the properties of modified layer were studied.

- Testing the chromized MFC under high magnetic field generation was carried out. The lifetime of the concentrators chromized at different conditions is about 30 pulses of 50 T peak field.

- The first results on new powder approach to develop a layered structure of steel have been obtained. Addition of 5% Cr to base powder leads to an increase in resistivity of base material by ~1.54 times.

Acknowledgements

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