SHIELDING MATERIALS AND PERSONAL GEAR FOR WELDER PROTECTION FROM MAGNETIC FIELDS

O.G. LEVCHENKO, V.K. LEVCHUK and **O.N. TIMOSHENKO**
E.O. Paton Electric Welding institute, NASU, Kiev, Ukraine

Issues related to development of personal protective gear for welder protection from magnetic fields in resistance welding are considered. Investigation results on protective properties of shielding materials made from magnetically soft strips of amorphous cobalt-base alloy (Co–Fe–Cr–Si–B) are presented. An apron has been developed to protect welders from electromagnetic radiation.

Keywords: *resistance welding, electromagnetic radiation, magnetic field intensity, protection methods, protective magnetic materials, permalloys and amorphous metal alloys, shielding apron*

Variable electromagnetic fields (EMF) of a broad frequency range and electromagnetic radiation of radiofrequency ranges are the main factors of hazardous impact on the body of electric welding operators. Application of special protective clothing could complement the known traditional methods of protection by time and space [1], as their realization is not always possible or rational in view of the scope and nature of operations performed by personnel.

The main component of electromagnetic background is low-frequency EMF, which is generated by power lines, household appliances and electrical equipment of industrial enterprises. It is known that electrical component of low-frequency field is readily shielded using metal sleeves and cases of distribution boards. However, shielding EMF magnetic component (that fully applies also to welding processes) is a complicated engineering task, if we are talking about elastic magnetic shields for personal protection gear (PPG) of the workers.

Table 1. Required effectiveness of protection from MF in resistance welding

Resistance welding process	Required effectiveness of protection at exposure for 8 h, times*
Spot:	
manual (tongs)	6–7**
mechanized stationary	3–4**
mechanized capacitor	2
Seam	2–3**
Projection	2–3**
Butt	2–3**

*Effectiveness of protective devices E_{sh} means a ratio of MF maximum amplitude intensity H_m in the work place to its TLV H_{th} ($E_{sh} = H_m/H_{th}$).
**Tentative value in welding with one pulse of full-wave current of up to 1 s duration.

Problems of shielding high-frequency magnetic fields (MF) in welding were studied at PWI [2], and methods to design electromagnetic shields have been developed [3–5]. However, parameters of intermittent-pulsed MF generated in welding, with allowance for their spectral composition, are so complicated that selection of effective shields for them can only be performed experimentally.

Experimental studies of magnetic radiation conducted by the authors [6, 7] at different electric welding processes showed that the highest MF level is characteristic of resistance welding, where the service personnel particularly needs PPG based on elastic magnetic shields. Tentative data obtained by us on the need for efficient protection of the welder in the working zone against MF using shielding at different resistance welding processes are shown in Table 1.

As is seen from the Table, maximum shielding effectiveness should lower MF intensity 7 times for an eight hour working day (MF frequency is equal to 0–1000 Hz). This is highly problematic for the known modern metallic shield materials, which should be solid and have sufficient elasticity. However, taking in account the fact that the net welding time during the working day is usually limited to 5 h, shielding efficiency can be reduced by approximately 1.3 times. Using the additional traditional methods of protection by time and distance, shielding effectiveness (to increase PPG elasticity at reduction of shielding layer thickness) can be reduced further by 2–3 times. Such a comprehensive approach to solving the problem of electromagnetic safety when using the procedure for MF level measurement developed at PWI yields positive results.

Development of PPG against low-frequency MF requires materials with high magnetic permeability ($\mu \geq 15000$) and high stability of magnetic properties. Complexity of development and manufacturing of shielding magnetic materials, which would be efficient both in the low- and in the high-frequency MF ranges, is related to the fact that their development makes it necessary to study various physical principles of operation and technological aspects of their manufacture. For instance for low-frequency MF (up to 1 kHz) the protective coating should be in the form of a continuous shell, and for high-frequency fields, measured in mega- and gigahertz, it is necessary to study the regular structure of the coating with gaps, the width of which is determined by the shielded field wave length.

Shielding material selection. Protective shielding in the general case is designed for protection both from MF, and from EMF. The versatility of such a solution, however, is not only dubious, but also not rational. Shields and coatings designed for protection from EMF and radiation of certain ranges of frequency and amplitude are considered to be the most suitable, as the magnetic properties of both the metallic and amorphous materials depend not only on their chemical composition, but also on their manufacturing conditions, modes of mechanical, heat and magnetic treatment. Selection of treatment modes allows manufacturing materials with the specified properties, the most efficient for EMF of certain ranges of frequency and amplitude. At development of such materials and their application as protective shields, it is necessary to determine the dependence of the coefficients of shielding or magnetic permeability on MF (EMF) amplitude-frequency characteristics and material treatment modes, providing maximum values of the above parameters at the manufacturing stage. In the first approximation, material magnetic permeability can be an indication of shielding properties of the selected material.

The most widely accepted materials for MF shielding are electric steels with 2.8–3.8 % Si made in the form of iron strips and sheets. Their magnetic properties are much higher along the rolling direction than in the transverse direction (magnetic permeability is up to 5000). Steel of 0.35–0.50 mm thickness is used at MF of 50 Hz frequency, and thinner steel — at MF of 400 Hz and higher frequency. Coefficients of shielding of these materials are not always satisfactory and depend on the modes of their preliminary heat treatment. In addition, if during manufacturing of parts (for instance, transformers), steel is subjected to even small plastic deformation (chipping, bending), its magnetic properties markedly deteriorate.

The most suitable thin shields for protection from MF generated by welding equipment are iron-nickel alloys (permalloys) and amorphous metal alloys with a high cobalt content [8]. Permalloys made in the form of sheets (or strips) 0.0015–2.5 and 3–22 mm thick contain from 45 up to 89 wt.% Ni. Alloys of 79NM, 80NKhS, 68NMP grades, which have up to 80 wt.% Ni (high-nickel permalloys), are used as magnetic shields. Letter P in the latter alloy grade indicates the rectangular shape of hysteresis loop and strong dependence of the alloy magnetic properties on the level of external MF. Permalloys have a high (up to 50000) magnetic permeability, but are highly sensitive to mechanical impact (work hardening). For instance, magnetic properties of a shield from permalloy of 79HM grade after its deformation by 10 % decrease by almost 18 times.

During the last decade considerable success has been achieved in the field of materials science, namely in development and putting into production of new polymer, composite and metallic materials with unique physical properties. One of the promising developments in this field is creation of new magnetically soft materials — amorphous metal alloys, which are characterized by a high magnetic permeability and saturation induction, and have various applications. The required physical properties of these materials can be achieved due to their heat and magnetic-thermal treatment. Predictable variation of magnetic properties, acceptable mechanical properties, as well as a constant lowering of the cost of manufacturing and pre-treatment of amorphous alloys, make them promising in development of elastic coatings for protection of personnel and technical means from MF and electromagnetic radiation of anthropogenic origin.

The composition of amorphous metal alloys suitable for practical application includes the main metals (iron, nickel, cobalt) and amorphoidizing additives (phospohorus, boron, silicon, carbon, aluminium). The most widely accepted materials are 85KSP and 71KNSP alloys with a high cobalt content [9]. Amorphous metal alloys are made in the form of very thin (down to several tens of microns) strips that is due to the technology of high-speed quenching (so-called spinning) of the melt.

It is known that the relative magnetic permeability of amorphous alloys can vary in a broad range. For instance, relative magnetic permeability of the high-cobalt alloy (80 wt.% Co) in MF with 10 kHz frequency and amplitude intensity $H_m = 800$ A/m after thermomagnetic treatment in a constant MF with the intensity of 1000 A/m at the temperature of 300 °C increases from 120,000 up to 300,000.

Analysis of the influence of the level of MF intensity on shielding properties of permalloy and high-cobalt amorphous alloy in MF of industrial frequency (50 Hz), depending on shielding materials with plant heat treatment, is given in [10], from which is follows that shielding efficiency of the above alloys is much higher than that of permalloy. It is also noted that at application of the same shielding materials, their properties are significantly improved with increase of MF frequency, even in low-frequency MF, the dependence of these properties on amplitude level of the latter becoming more complicated.

Thus, one of the main problems, arising in development of systems of electromagnetic shielding, consists in that the range of MF frequency, in which modern technical devices operate, is very broad, and protective materials ensure shielding in just a limited frequency range. As was noted earlier, such materials as permalloy, are highly sensitive to mechanical impacts. In amorphous metal alloys, as a rule, high uniaxial magnetic anisotropy is realized, however, the amorphous state is metastable. In this connection, amorphous materials are characterized by the ageing effect, particularly, at increased temperature.

Investigations conducted at TsNII CM «Prometey» (RF) showed that amorphous magnets of one grade, but from different manufacturers, differ essentially in their magnetic properties. As Ukraine has both the scientific-technical and production facilities for manufacturing amorphous magnets (G.V. Kurdyumov Institute of Metal Physics of the NAS of Ukraine and MELTA Ltd., Kiev), development of protective structures and overalls similar to foreign developments, is not always rational.

The above-said leads to the conclusion that at present there is no universal solution for ensuring electromagnetic shielding of specific objects. Taking organizational-technical decisions on electromagnetic shielding requires thorough theoretical and experimental studies of the processes of thermal and magnetothermal treatment of amorphous materials to optimize their properties for application as magnetic and electromagnetic shields. At present amorphous alloys can be regarded as the most promising materials for protection of technical and biological objects from adverse influence of MF and electromagnetic radiation. Development of elastic protective shields for electromagnetic devices and protective clothing should be oriented to local magnetically soft materials.

Development of elastic magnetic shield for welder's protective clothing. During performance of welding operations the following harmful and hazardous production factors are in place: sparks and spatter of molten metal and slag with up to 2000 °C temperature, radiant energy from the welding arc of different spectral composition and intensity, thermal radiation of up to 84 $J/(cm^2 \cdot min)$ ($20\ cal/(cm^2 \cdot min)$), MF of 80–10000 A/m intensity of 0–2000 Hz frequency, dust and fume levels in welder breathing zone with harmful substance concentration exceeding the TLV, meteorological factors, when working in open air, depending on the season and climatic zone.

In keeping with the labour conditions and nature of impact of these harmful and hazardous factors, all the clothing for welding fabrication workers is divided into five groups based on the common protective, service and hygienic properties. By the earlier existing classification the protective clothing for resistance welding of metal of small cross-sections (spot, seam, projection and butt welding) was classified as group 3A, and was to provide protection from MF of 80–10000 A/m intensity (amplitude value) without indication of any frequency ranges. Welder's PPG should include suit (coat and trousers), gloves and mittens, headwear and footwear [11, 12].

A protective outfit is known which consists of a cap and short skirt [12], where permalloy of 79NM-I, 80NKhS, 76NKhD grades was used in the form of thin metal threads mixed with cotton threads, which protect from external impact and act as electrical insulation. Thus, a cloth with a regular structure forming a net with 0.5 × 0.5 mm mesh was used as the shield. There is a lack of data on shielding properties of such a material designed for protection from low-frequency MF, and its effectiveness is highly doubtful.

PWI staff had the goal of developing a protective magnetic shield that could be the basis for welder's protective clothing, allowing for the modern sanitary norms of magnetic safety. Here, it was to be decided what is the meaning of «elasticity» term for protective clothing. Elasticity (from the Greek for flexible) is the ability of a structural material or product to stand considerable elastic reversible deformations without fracture at relatively small loads. The term «elasticity» exists side by side with the term «resilience». Elasticity is achieved both through selection of material (for instance, rubber), when it is due to the features of the molecular structure of the body, and due to design. In the latter case high deformations of the item develop at small material deformations. It is the issue of conditional use of «elasticity» term for composite material for the protective clothing, which essentially is a functional material and ensures MF shielding in addition to the traditional properties of protective clothing. The need to include a metal layer into the composition of protective clothing material, and possibly, also additional functional layers (electrically insulating, protective, adhesive, etc.), as a rule, lowers such a parameter as flexibility, the limit value of which is equal to 0.50–0.55 kN for textiles, designed for protective coverplates, stripes, etc. [13].

Tentative structure of a material for protective clothing should have the following component layers-parts: one or two inner layers of the magnetic shield; two external electrically-insulating layers (if required); two external layers from a material traditional for this type of protective clothing; two inner layers (or a coating) of a technological purpose (for instance, adhesive).

Known is an engineering solution for protective clothing against MF [9], in which the shield is formed by longitudinal strips of an amorphous alloy with overlaps across the width, thus providing a continuous protective shielding coating of the textile. The method of strip joining to each other and to the textile was not considered in this work, but in any case it promotes an increase of rigidity of the shield design, both in the longitudinal and in the transverse directions, as a result of rigid fastening of individual layers into a whole. In our opinion more promising is the design of an elastic magnetic shield, consisting of strips, which are connected to each other due to their so-called linen weave with zero gaps between the strips located in one direction without a rigid connection to each other. In this case the structure is completed without using any additional materials or elements during shield assembly. It provides the maximum magnetic shielding in two directions normal to each other (in connection with the anisotropy of magnetic properties of the strip).

The required protective properties can be obtained at the expense of increase of the total number of shields in the pack or strips woven in one shield without a rigid connection to each other. In this case use of several shields from single strips is preferable, as a result of their assembly into a pack with the shifting of points and lines of intersection of strips in one shield relative to the other the total effective thickness of the latter is increased, and its continuity for magnetic lines of force is ensured at maximum possible elasticity. Contacting of shield strips and individual shields with each other occurs both due to weaving, and due to elastic properties of the material and its certain residual magnetization. With reduction of the width and thickness of the composite strips of the shield its elasticity increases, but the labour consumption in its manufacture increases at the same time, which is not of principal importance, considering the urgency of the problem.

It is anticipated that the number of woven shields in the pack will not exceed two. If the double shield does not provide a sufficient level of protective properties, increase of shielding effectiveness can be achieved through additional thermomagnetic treatment of the strips that will increase the effectiveness further approximately by 2 times. However, mechanical properties of the shield material (in particular, number of bending cycles) deteriorate as a result of such a treatment. In this connection, it is initially intended to manufacture these shields from a material with a minimum (up to 70 %) content of deficit cobalt and without additional thermomagnetic treatment.

Available numerous data on the dependence of magnetic features of magnetically soft alloys on the level of external MF and coefficients of shielding for materials with different treatment conditions often are contradictory and need more precise definition. Reliable data on the dependence of coefficients of shielding of low-frequency range (0–1000 Hz) of external continuous or pulsed MF are also absent.

Experimental study of protective properties of shields in the laboratory. The main characteristic of a protective shield is the shielding effectiveness E_{sh}, which includes the relationship of electric field intensity E, magnetic field intensity H or power flow density (PFD) in a given point in the absence of a shield and E_{sh}, H_{sh} or PFD in the same point in the presence of a shield:

$$\mathrm{E}_{\mathrm{sh}} = \frac{E}{E_{\mathrm{sh}}} = \frac{H}{H_{\mathrm{sh}}} = \frac{\mathrm{PFD}}{\mathrm{PFD}_{\mathrm{sh}}}.$$

It is rational to determine protective properties of materials experimentally by measurement of MF level behind the protective shield, as described in [10]. Diagram of a laboratory facility for testing pilot samples of shields is given in Figure 1.

MF generator allows in the first approximation simulating continuous MF with the spectral composition and intensity, characteristic for the working zone in resistance welding. Relative position of the generator, MF sensor and shield-partition in the experiments (allowing for the model scale factor) can be taken to be arbitrary, therefore, measurement of the intensity of the initial MF and field behind the shield was conducted in three planes normal to each other, which was followed by calculation of the resultant MF value (geometrical mean). Note that the effectiveness of the shield-partition theoretically is lower than that of protective clothing in the form of open or closed cylinder. However, this factor is not critical, considering that model studies were preliminary and comparative, and the final test of shielding effectiveness is conducted with samples of protective clothing in the shop.

Integral effectiveness of shielding in keeping with sanitary norms [14] was experimentally determined as

$$\mathrm{E}_{\mathrm{sh}} = \frac{\sum_{n} H^2_{1\,mn}}{\sum_{n} H^2_{2\,mn}},$$

where $H_{1\,mn}$, $H_{2\,mn}$ is the amplitude dependence of initial MF and that beyond the shield, respectively.

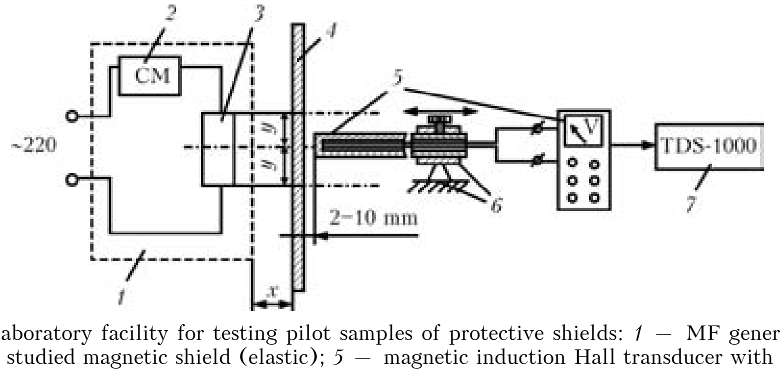

Figure 1. Schematic of a laboratory facility for testing pilot samples of protective shields: *1* — MF generator; *2* — control module (CM); *3* — solenoid; *4* — studied magnetic shield (elastic); *5* — magnetic induction Hall transducer with conversion; *6* — fastening of magnetic induction sensor; *7* — digital storage oscilloscope with the function of fast Fourier transformation (x, y have variable values)

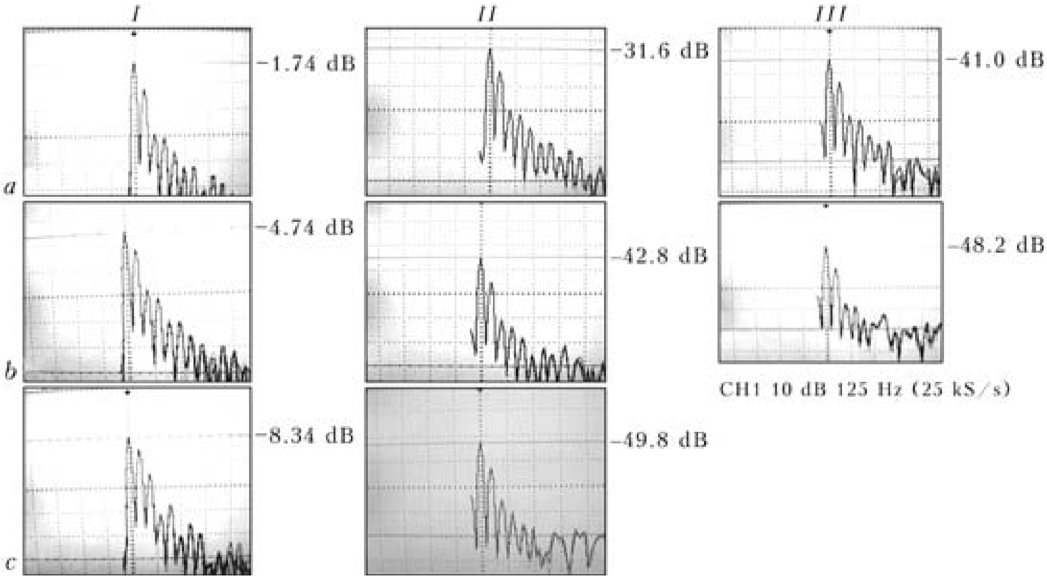

Figure 2. Nature of weakening of output MF by experimental shields: *a* — manual spot welding, H_m = 14000 A/m ((by the first 50 Hz harmonics); *b* — spot welding in stationary machines, H_m = 420 A/m; *c* — projection, seam, butt welding, H_m = 150 A/m; *I–III* — without the shield, with single and double shields, respectively

Here it was taken into account that the distance between the sensor plane and the shield equal to 2–10 mm (see Figure 1), corresponds to the actual gap between the human body and the shielding protective clothing [15].

Spectrographs (Figure 2) of MF of various intensities show the nature of differential weakening of each MF harmonics by open experimental single and double shields from strips of an amorphous metal alloy MM-5Co (Co–Fe–Br–Si) of width b = 27.5 mm and thickness δ = 0.0225 mm, assembled using linen weave. At small distances between the shield and sensor MF intensity in each of the points located along the shield strips, periodically changes slightly, reaching a minimum directly above the strips. Therefore, MF intensity was determined as the arithmetic mean of three values of intensity, measured directly under the strips of a single- (δ = 0.045 mm) and two-layer (δ = = 0.09 mm) shield, as well as in the middle between adjacent strips of different directions (δ = 0.0225 and 0.045 mm, respectively) and in the nodal points of the weave (δ = 0 and 0.045 mm, respectively).

Preliminary results of laboratory studies (Tables 1, 2) indicate that experimental shields have a certain reserve of shielding effectiveness in operation in MF, similar to fields, which form in the considered resistance welding processes, except for manual spot welding with MF intensity $H_m > 1000$ A/m (by the first 50 Hz harmonic). At operation of resistance welding machine with a manual tool (tongs) effectiveness of MF shielding using this shield does not provide the required protection of the welder.

Comparison of the data in Tables 1 and 2, as well as general considerations set forth in this work, allow selection of a single-layer shield with linen weave of the strips.

Thus, shielding layer in protective clothing from Ukrainian magnetically soft amorphous cobalt-based metal alloys (Co–Fe–Cr–Si–B) with sufficient mechanical functionality, can generally provide the necessary level of protection of the welder in the immediate working zone when using a product in the form of an elastic open shield in MF of medium intensity

Figure 3. Test sample of welder's protective apron without a lining (reverse side view)

Table 2. Anticipated effectiveness of experimental elastic shields with the main resistance welding processes

Resistance welding method	Effectiveness of protection by a shield with linen weave of strips, times	
	Single-layer	Double-layer
Spot:		
manual (tongs, guns)	1.2	2.0
mechanized stationary	14.4	26.0
Seam	4.4	18.4
Projection		
Butt		

($H_m \leq 500$ A/m by the first 50 Hz harmonic) in the frequency range of 500–1000 Hz.

Proceeding from the performed research, a functional sample of protective apron for the welder (Figure 3) [16] for operation in stationary machines for resistance welding with vertical location of electrodes (spot, seam, projection, capacitor, etc.) was manufactured. Testing of the shielding apron under production conditions at spot welding in MT-2202 machine demonstrated results similar to those obtained in laboratory experiments.

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