ArcelorMittal

AFK 502 R – AFK 1 – AFK 18
Fe-Co SOFT MAGNETIC ALLOYS

I GENERAL ASPECTS

The recent marked development of electrical engineering equipment has led to an increasing demand for the miniaturization of ancillary devices for the production and transformation of electric power. This is particularly true for on-board electrical systems in aircraft, trains and road vehicles.

The power/weight ratio of such systems can be optimized by the use of Fe-Co soft magnetic alloys, whose exceptional properties include:

- A high saturation induction, the highest of all known magnetic alloys.
- Useful permeability at working inductions greater than or equal to 1.6 T, compared to those of commonly employed magnetic materials, such as soft iron and iron-silicon alloys.
- A sufficiently high electrical resistivity in AFK 502 R (Rotor grade) to ensure the reduction of losses for alternating current and high induction levels.
- A Curie point between 950 and 980℃, such that the magnetic properties are little changed at temperatures of 250 to 500℃, a considerable advant age for high temperature applications.

The induction-applied field curves illustrated in Figure 1 demonstrate the superiority of the AFK grades over Fe-Si alloys at high inductions. They can be used to roughly estimate the potential gains in cross section, weight and space requirements.

Furthermore, it should be noted that these Fe-Co sheets can be readily stamped before final heat treatment with reduced cutting tool wear compared to that observed with Fe-Si alloy sheets.

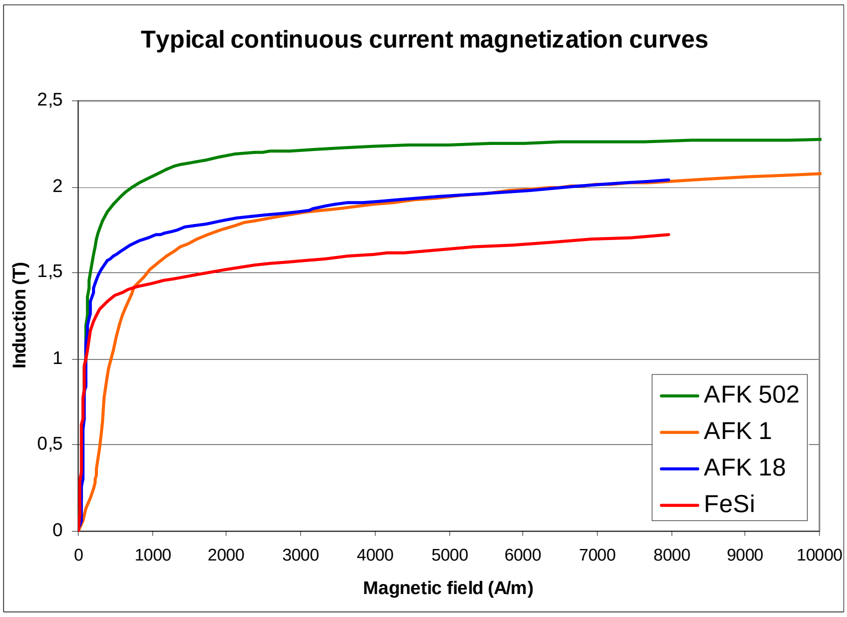

Figure 1 : Initial DC magnetization curve B = f (H)
at ambient temperature measured on 0.35 mm thick rings.

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On request, the measurement points can be made available to customers in computer format.

Following extensive studies, Imphy Alloys has developed a series of iron-cobalt alloys with cobalt contents from 18 to 49%, together with minor additions of other alloying elements, such as chromium or vanadium. The role of the latter is both to increase their ductility and hence facilitate processing (forging and cold rolling) and to enhance their electrical resistivity.

The Fe-Co grades produced by Imphy alloys can be divided into three groups depending on their Co content:

Element (wt %) Alloy	Fe	Co	V	Cr	Mn
AFK 502 R	Balance	49	2		
AFK 1	Balance	27		0.5	0.3
AFK 18	Balance	18			0.3

AFK 502 R has a slightly lower saturation induction than AFK 1, combined with a much higher permeability at medium field strengths. Its resistivity is double that of AFK 1.

AFK 1 has the highest saturation induction, but its permeability and resistivity are lower than those of AFK 502. It is particularly suited for DC applications, such as poles for electromagnets and mass spectrographs, and more generally, for various components operating at high induction levels.

AFK 18 has a lower cobalt content and, in terms of composition, lies in an intermediate position between the Fe-Si grades and AFK502 R. It combines high saturation and working induction levels due to the presence of cobalt, an electrical resistivity close to those of AFK502R and Fe-3% Si, mechanical strength similar to AFK502R, a magnetostriction significantly lower than that of AFK502R and close to Fe-Si, and a good aptitude for forming (stamping, punching, bending, deep drawing, etc.) in both the cold worked and annealed conditions. In the latter respect, its formability is very close to that of the Fe-Si alloys.

All these grades are suitable for AC applications, such as high power density motors, generators and supply transformers.

Their high magnetostriction coefficient also makes them an appropriate choice for magnetostrictive transducer cores.

II FINAL HEAT TREATMENT

The aim of the heat treatment, which must be performed on the finished parts, is to eliminate internal stresses due to cold work and to give the metal the required balance between magnetic and mechanical properties.

II.1. Part preparation

It is recommended, particularly for thin components, to thoroughly degrease the surfaces before heat treatment to avoid all risk of surface contamination.

Furthermore, to prevent the components from sticking together during heat treatment, it is preferable to coat them with a film of inert anhydrous material, such as talc, magnesia or alumina.

For heavy parts, it is necessary to provide flat supports adapted to the shape and weight of the components, in order to avoid distortion during heat treatment.

II. 2. Heat treatment atmosphere

The treatment must be performed out of contact with oxygen, either in pure dry hydrogen or under vacuum. Cracked ammonia atmospheres are acceptable only for AFK1 and AFK18, but not for AFK502R, in which nitriding is observed, leading to a marked impairment of the magnetic properties.

II. 3. Recommended cycles

It should be pointed out that the temperatures indicated below must not be exceeded, since otherwise the properties will be irremediably degraded. This occurs immediately on attaining the temperature of the α ⇆ γ allotropic transformation, situated at around 900°C for AFK502R and AFK1 and 940℃ for AFK18.

Grade	Typical heat treatment
AFK 502 R	➢ Treatment for optimizing the magnetic properties: 2 to 3 h at 850℃ in pure dry hydrogen or under vacuum, followed by cooling at 250℃/h in the same atmosphere. To reduce the treatment time, cooling can be performed in air below 300℃. ➢ Treatment for optimizing the mechanical properties: 2 to 3 h at 725℃ in pure dry hydrogen or under vacuum, followed by cooling at 250℃/h in the same atmosphere. To reduce the treatment time, cooling can be performed in air below 300℃.
AFK 1	➢ Treatment for optimizing the magnetic properties: 2 to 3 h at 850℃ in pure dry hydrogen or cracked ammonia, followed by cooling at 250℃/h in the same atmosphere. ➢ Treatment for optimizing the mechanical properties: 2 to 3 h at 725℃ in pure dry hydrogen or cracked ammonia, followed by cooling at 150℃/h in the same atmosphere.
AFK 18	1 to 4 h at 900℃-920℃ in an atmosphere of pure dr y hydrogen, or under vacuum or in an inert atmosphere (rare gas), followed by cooling in the same atmosphere.

In the heat-treated condition, all magnetic materials must be handled with care, avoiding shocks and plastic deformation. These precautions are particularly recommended for AFK502R alloy, whose deformation capacity is limited.

After heat treatment, the metal shows a dimensional expansion $\frac{\Delta\ell}{\ell}$ of the order of 1 to 1.5 x 10^{-3}.

This must be allowed for in particular cases where the components must respect tight tolerances.

III TYPICAL MAGNETIC PROPERTIES

The magnetic properties are given at ambient temperature, in the complete absence of mechanical stresses. Any strain, even elastic, will impair the magnetic properties. However, in the case of purely elastic strain, the metal will recover its initial properties as soon as the strain is removed.

III.1 AFK 502 R

III.1.1 AFK502R cold rolled strip

Property	Units	AFK 502 R
Saturation induction	Tesla	2.35
Resistivity at 20℃	μΩ.cm	40
Curie point	℃	900
Density	$g.cm^{-3}$	8.12
Mean CTE between 0℃ and 100℃	10^{-6}.℃ $^{-1}$	9.5
Mean CTE between 0℃ and 300℃	10^{-6}.℃ $^{-1}$	9.5
Mean CTE between 0℃ and 500℃	10^{-6}.℃ $^{-1}$	9.8
Thermal conductivity between 0℃ and 100℃	$W.m^{-1}$.℃ $^{-1}$	29
Thermal conductivity between 0℃ and 300℃	$W.m^{-1}$.℃ $^{-1}$	32
Thermal conductivity between 0℃ and 500℃	$W.m^{-1}$.℃ $^{-1}$	35
Coefficient of magnetostriction at saturation $\frac{\Delta\ell}{\ell}$	10^{-6}	60 – 70
Young's modulus for non-annealed cold rolled strip	MPa	210 000 – 220 000
Young's modulus for annealed cold rolled strip	MPa	180 000 – 200 000

The tables below give the magnetic properties obtained for three heat treatments, to be used depending on the desired compromise between magnetic and mechanical properties. The measurements were performed on 36*25*0.35 mm rings (outside diameter*inside diameter *thickness).

Magnetic losses (W/kg)				
Measurement conditions	**f = 50 Hz**		**f = 400Hz**	
	B = 1.5 T	**B = 2 T**	**B = 1.5 T**	**B = 2 T**
Heat treatment				
2 h at 725℃ cooling at 250℃/h			51.9	91.3
2 h at 750℃ cooling at 150℃/h	3	5	44	84
3 h at 850℃ cooling at 250℃/h	2.3	3.8	42.1	73.6

III.1.2 AFK 502 R bar (massive)

DC magnetization characteristics					
Heat treatment	**B (Tesla) at 800 A/m**	**B (Tesla) at 1600 A/m**	**B (Tesla) at 4000 A/m**	**B (Tesla) at 8000 A/m**	**Hc (A/m)**
2 h at 760℃ under H2, cooling at 200℃/h	> 1.8	>2	>2.2	>2.25	160
3 h at 850℃ under H2, cooling at 250℃/h	> 2	>2.1	>2.2	>2.25	110
6 h at 870℃ under vacuum, cooling at 250℃/h	> 2	>2.15	>2.2	>2.25	80

III.2 AFK 1 cold rolled strip.

Property	Units	AFK 1
Saturation induction	Tesla	2.4
Resistivity at 20℃	µΩ.cm	20
Curie point	℃	980
Density	$g.cm^{-3}$	8
Mean CTE between 0℃ and 100℃	10^{-6}.℃$^{-1}$	10.3
Mean CTE between 0℃ and 300℃	10^{-6}.℃$^{-1}$	10.3
Mean CTE between 0℃ and 500℃	10^{-6}.℃$^{-1}$	11
Thermal conductivity between 0℃ and 100℃	$W.m^{-1}$.℃$^{-1}$	46
Thermal conductivity between 0℃ and 300℃	$W.m^{-1}$.℃$^{-1}$	67
Thermal conductivity between 0℃ and 500℃	$W.m^{-1}$.℃$^{-1}$	84
Coefficient of magnetostriction at saturation $\frac{\Delta\ell}{\ell}$	10^{-6}	30-35

The tables below give the magnetic properties obtained for two heat treatments, to be used depending on the desired compromise between magnetic and mechanical properties. The measurements were performed on 36*25*0.35 mm rings (outside diameter*inside diameter *thickness).

DC magnetization characteristics					
Heat treatment	**B (Tesla) at 800 A/m**	**B (Tesla) at 2000 A/m**	**B (Tesla) at 8000 A/m**	**B (Tesla) at 16000 A/m**	**Hc (A/m)**
2 h at 725℃ cooling at 150℃/h	>1.47	>1.73	>2.02	>2.19	200
3 h at 850℃ cooling at 250℃/h	>1.47	>1.73	>2.02	>2.19	95

III.3 AFK 18 cold rolled strip

Property	Units	AFK 18
Saturation induction	Tesla	2.3
Resistivity at 20℃	μΩ.cm	30
Curie point	℃	940
Density	$g.cm^{-3}$	7.9
Mean CTE between 0℃ and 100℃	$10^{-6}.℃^{-1}$	10.5
Mean CTE between 0℃ and 300℃	$10^{-6}.℃^{-1}$	10.5
Mean CTE between 0℃ and 500℃	$10^{-6}.℃^{-1}$	11.2
Thermal conductivity between 0℃ and 100℃	$W.m^{-1}.℃^{-1}$	57
Thermal conductivity between 0℃ and 300℃	$W.m^{-1}.℃^{-1}$	67
Thermal conductivity between 0℃ and 500℃	$W.m^{-1}.℃^{-1}$	84
Coefficient of magnetostriction at saturation $\frac{\Delta\ell}{\ell}$	10^{-6}	21-26

The tables below give the magnetic properties obtained for two heat treatments, to be used depending on the desired compromise between magnetic and mechanical properties. The measurements were performed on 36*25*0.35 mm rings (outside diameter*inside diameter *thickness).

Heat treatment	B (Tesla) at 2500 A/m	B (Tesla) at 5000 A/m	B (Tesla) at 10000 A/m	Hc (A/m)
2 h at 700℃ cooling at 250℃/h	> 1.75	>1.85	>2	150
2 h at 900℃ cooling at 250℃/h	> 1.75	>1.85	>2	60

Magnetic losses (W/kg)				
Measurement conditions	**f = 50 Hz**		**f = 400Hz**	
	B = 1.5 T	**B = 1.7 T**	**B = 1.5 T**	**B = 1.7 T**
Heat treatment				
2 h at 700℃ cooling at 250℃/h	5.5	6.7	77	99
2 h at 900℃ cooling at 250℃/h	3.3	4.3	66	88

IV TYPICAL MECHANICAL PROPERTIES

Like all the other magnetic alloys, the AFK grades have a low capacity for deformation in the cold worked (non annealed) condition. However, for AFK502R, the usual annealing treatment does not completely regenerate the deformation capacity, which remains fairly low, as indicated by the elongation (El %) values in the tables below. This low strain capacity increases the uncertainty in the measured proof stress (0.2% PS) and ultimate tensile stress (UTS) values, **which are therefore only indicative in nature**. Although the absolute elongation values are small, these levels prove to be sufficient to enable the production of the sheet components that are assembled and used to produce motors meeting civil and military aviation requirements.

Moreover, it is possible to improve the ductility of AFK502R by annealing below 760℃, followed by cooling at an appropriate speed. However, since the gain in elongation is obtained at the expense of the magnetic properties, and since the annealing treatment corresponding to optimum formability is difficult to perform, it should only be envisaged in quite exceptional circumstances.

IV.1 Mechanical properties on cold rolled strip

The data below represent typical values at ambient temperature for measurements made according to the standards:

- NF EN 10002 for tensile tests
- EN ISO 6507 for hardness measurements

AFK 502 R - thickness 0.35mm				
Heat treatment	**UTS (MPa)**	**0.2% PS (MPa)**	**El%**	**Hardness**
Cold worked condition	1200	1150	2	400
2 h at 725℃ cooling at 150℃/h	715	450	7.5	255
2 h at 750℃ cooling at 150℃/h	600	400	5.5	240
3 h at 850℃ cooling at 250℃/h	480	300	4.5	220

AFK 1 - thickness 0.35mm				
Heat treatment	**UTS (MPa)**	**0.2% PS (MPa)**	**El%**	**Hardness**
Cold worked condition	1000	900	2	300
2 h at 725℃ cooling at 150℃/h	600	350	17	190
3 h at 850℃ cooling at 250℃/h	510	250	13	180

AFK 18 - thickness 0.35mm				
Heat treatment	**UTS (MPa)**	**0.2% PS (MPa)**	**El%**	**Hardness**
Cold worked condition	850	800	2	310
2 h at 700℃ cooling at 250℃/h	470	355	29	185
2 h at 900℃ cooling at 250℃/h	380	210	31	175

V DELIVERY FORMATS

Grade	Treated cores (1)	Treated parts (1)	Cold rolled strip	Long and massive products (2)
AFK 502 R	▪	▪	▪	▪
AFK 1	▪	▪	▪	▪
AFK 18	▪	▪	▪	▪

(1): cores, profiles, stacked laminations, rotor and stator sheets, plates for chemical machining sold by MECAGIS, a subsidiary of Imphy Ugine Précision, like Imphy Alloys
(2): bars, profiled sections, forgings, hot rolled sheet

The AFK alloys can be delivered :

- As cold rolled strip in the cold rolled condition for AFK 1, AFK 502 R and AFK 18

This is the common choice when users wish to machine or stamp parts from intermediate plates, rounds, or strips. The heat treatment must be performed on the parts when all the mechanical operations have been completed.

Strip can also be delivered with an insulating film of magnesium methylate.

- As cold rolled strip in the annealed condition for AFK 18
This condition is useful when users prefer to stamp or machine components from the strip and to mount them directly in electrical devices without performing a final heat treatment to optimize the magnetic properties. The annealed condition delivered can be satisfactory when the magnetic material operates at saturation or under strong magnetic field pulses.

- In the form of ready-to-use heat treated parts for AFK 1, AFK 502 R and AFK 18
Mécagis, a subsidiary of Imphy Ugine Précision like Imphy Alloys, can provide pre-stamped parts and wound cores, heat treated to optimize the required properties.

V.1 Flat products

The tables below indicate the standard delivery formats

AFK502 R			
Format	**Thickness (mm)**	**Maximum width (mm)**	**Condition**
Cold rolled strip delivered in coils	0.1 – 0.5	200	Cold worked
	1-1.3	50	Cold worked
Hot rolled strip	5 to 50	500 to 2 000	As-rolled and pickled

AFK 1			
Format	**Thickness (mm)**	**Maximum width (mm)**	**Condition**
Cold rolled strip delivered in coils	0.1 – 0.5	300	Cold worked
	1-1.3	50	Cold worked
Hot rolled strip	5 to 50	500 to 2 000	As-rolled and pickled

AFK 18			
Format	**Thickness (mm)**	**Maximum width (mm)**	**Condition**
Cold rolled strip delivered in coils	0.1 – 0.5	300	Cold worked or annealed
	1-1.3	50	Cold worked
Hot rolled strip	5 to 50	500 to 2 000	As-rolled and pickled

* Note :

Because of their limited deformation capacity and the risk of fracture in the absence of adequate support, small diameter rods and thin plates cannot be supplied in long lengths for the AFK 502 R grade. If long lengths are essential, it is recommended to choose larger thicknesses or diameters.

V.2 Bars

AFK 502 R – AFK 1 – AFK 18	
Diameter ϕ (mm)	**Standard lengths (mm)**
ϕ ≤ 13	2000 to 3000
14 ≤ ϕ ≤ 80	3000 to 4000
ϕ > 80	Depends on the diameter and the quantity ordered

V.3 Forgings and castings

Please consult us for estimates

VI IMPLEMENTATION

VI.1 Shaping and machining

The AFK alloy strips can be sheared and cut, but because of their low ductility, they cannot be deep drawn. However, AFK 1 strip can be bent.

The following machining conditions are recommended for the AFK alloys:

		AFK 18	AFK 1	AFK 502
Turning	**Tools** **Coolant** **Cutting angle** **Rake angle** **Cutting speed**	Carbide Soluble oil 10° 4° 50 -150 m/min	Carbide Soluble oil 8° 4° 55 - 100 m/min	Carbide Soluble oil 10° 4° 50 -150 m/min
Milling	**Tools** **Coolant** **Advance speed** **Cutting speed**	High speed steel Soluble oil 0.08 – 0.10 mm/tooth 40 – 150 m/min	High speed steel Soluble oil 0.05 – 0.07 mm/tooth 15 – 40 m/min	High speed steel Soluble oil 0.08 – 0.10 mm/tooth 20 - 50 m/min

The low ductility of these materials leads them to behave like certain carbon steels, requiring similar precautions, such as the need to avoid mechanical or thermal shocks, or large amplitude vibrations.

VI. 2. Welding and brazing

Welding and brazing of AFK502R requires special precautions. Thus, the temperatures involved and the subsequent slow cooling cause a loss of toughness in the transition zones adjacent to the welds, together with a drop in mechanical strength. Furthermore, care must be taken to avoid loss of vanadium in the form of oxide or nitrate, since this would lead to a further reduction in ductility and local impairment of the magnetic properties. Indeed, welding and brazing of AFK502R is to be avoided whenever possible. The AFK1 grade does not suffer from these problems, and should be preferred when such joining operations are essential.

However, if electron beam welding is technically possible, it provides a solution for overcoming the above difficulties.

In the case of brazing, an appropriate choice of braze metal is necessary to prevent the risk of stress corrosion cracking, together with parts completely free from residual tensile stresses. The parts must therefore have been previously baked at a relatively high temperature, or annealed.

VI. 3. Soft soldering

Soft soldering is possible only on parts that have undergone the final heat treatment.

To ensure optimum soldering conditions, it is essential to carefully clean and pickle the surfaces. For example, zinc chloride pickling can be performed using the following solution:

Zn .... 380 g
HCl 22°Bé .... 1 000 cm^3