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Monotonic and cyclic behavior of Cu-Ni-Si precipitation-hardened alloy used for magnetic pulse technologies.

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ABSTRACT

The compromise mechanical characteristics-electrical conductivity comes first to determine the employment possibilities for precipitation hardening copper alloys. The Cu-Ni-Si alloy as a precipitation hardened alloy exhibits high mechanical characteristics and moderate electrical conductivity. The present work is based on two parts, in the first we studied alloy tensile behavior, in the second we are interested in material response at high cycle fatigue. Cu-Ni-Si has a very good tensile strength of 646 MPa; it displays a very wide plasticizing phase in monotonic stress. Furthermore, the Cu-Ni-Si alloy gives good fatigue resistance in law cycle fatigue as well as in high cycle fatigue with a fatigue limit of 210 MPa.

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Introduction:

To reduce weight and perform functionalities, parts and structures are increasingly made from different materials. The diversity of the combined materials properties is practically a challenge for the assembly technologies [1].

Magnetic pulse technology is used in several manufacturing processes (welding, forming, crimping, etc.).This attractive technology is particularly different from conventional methods in terms of cost, reliability, ease of manufacture and work speed. It offers the highest production rate, a better yield and is considered a green and clean process [2].

The magnetic pulse process uses a standard electrical source and magnetic parts mainly a coil and a field shaper (auxiliary part).These magnetic tools must have a very good compromise between electrical conductivity and mechanical strength [3], this mission is performed byprecipitation hardening copper alloys. Structural hardening by precipitation consists in precipitating by quenched and tempered heat treatment process the second-phase particles in the grains of the alloy [4-6]. These precipitates impede the movement of the dislocations in sliding plans and improve so the mechanical strength [7].

However, the cyclical passage of the current in the magnetic parts induces a stress periodic distribution and therefore a damage fatigue. In this work we study the monotonic and cyclic behavior of a structural hardening copper in order to understand his degradation mechanism and to estimate the lifetime of the magnetic parts. The material studied is a Cu-Ni-Si alloy with 96.9% Cu with 2.5% Ni in percentage weight and displays an electrical conductivity of 45% IACS.

Material and method:

Monotonic tensile tests:

Tensile tests were carried out on Cu-Ni-Si (96.9% Cu, 2.5% Ni and 0.6% Si) in order to determine the main mechanical characteristics. They were executed on flat test pieces prolonged on either side by attaching heads of suitable shape for fixing. The specimens fixed to the tensile machine are subjected to a uniaxial force. The extensometer is attached between the two locating points defining the useful part of the specimen L_0(where the stress state is homogeneous).The specimen geometry is illustrated in Fig.1.

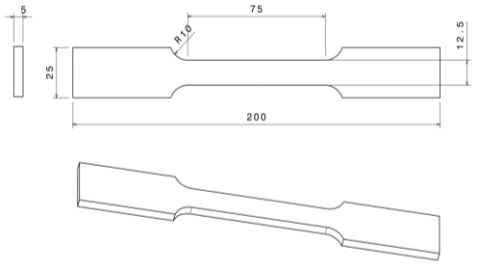

Fig: 1. Tensile test specimen geometry

The samples were taken in two directions and with two different thicknesses, the direction of rolling (long direction) and the transverse direction (perpendicular direction).For the 35 mm thickness, the specimens were machined, while for 5 mm thickness, a block was machined and the thickness was made by wire cutting.

Cutting direction and specimen thickness combination leads to 4 tests series, for each test a batch of 4 or 5 samples was prepared. The repetition of tests aims to good reproducibility.

Fatigue tests:

The fatigue tests are carried out on an MTS biaxial hydraulic machine model 17 (Fig.2). The assembly consists of a rigid frame carrying an adjustable cross-bar. On the lower part of the frame, two hydraulic cylinders ensure the loading of the specimens. On the moving cross-bar, there are two measuring cells, one for determining tensile-compression forces up to ± 50kN; and the other for measuring the torsional torque.

To achieve fatigue testing, we chose classical shape specimens with circular section and high cycle number (according to ASTM E466-07) (Fig.2).

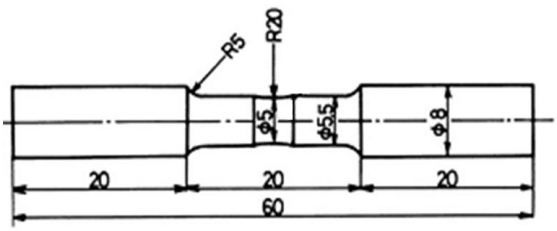

Fig:2. Fatigue specimen geometry

Fatigue results of Cu-Ni-Si show an important dispersion. This results dispersion of fatigue tests is now considered to be one of the fatigue physical aspects [8]. Indeed, for the same material and for the same load level, lifetime may differ.

Results and discussions:

Tensile behavior:

The reproducibility conditions of the experimental tests are verified despite a low dispersion observed at failure strain. This tests reproducibility is a strong point for our cuprous law behavior characterization (Fig.3). The anisotropy examination (Fig.4) shows a very light offset between the tensile curve in the long direction and that in the perpendicular direction for 5 mm thickness samples. This difference disappears for 35 mm samples thickness. The tensile behavior of Cu-Ni-Si is almost identical for both taking directions.

The thinnest sample exhibits the best mechanical strength in uniaxial tensile. The thickness effect is very notable (Fig.5). During tensile tests, the Cu-Ni-Si alloy retains the upper mechanical strength for the low thickness value. The difference is interesting at the yield strength; it decreases by 20% for 35 mm thickness. The plastic domain is not impacted by thickness effect. In any direction, failure strains observations indicate very sensitive difference between the two studied thicknesses. In Table 1, we summarized the optimum mechanical characteristics of the studied alloy.

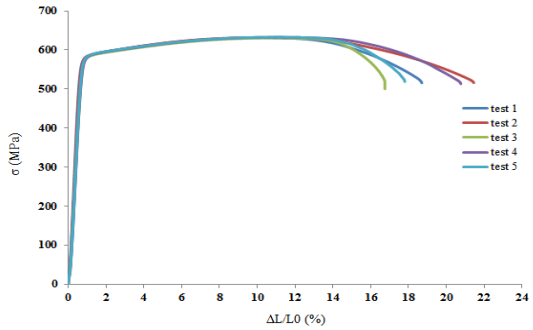

Fig: 3. Reproducibility of Cu-Ni-Si tensile tests

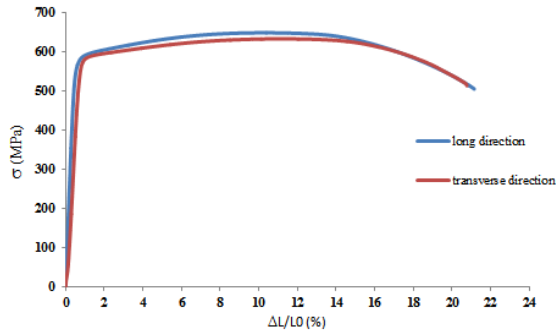

Fig:4. Cu-Ni-Si anisotropyverification

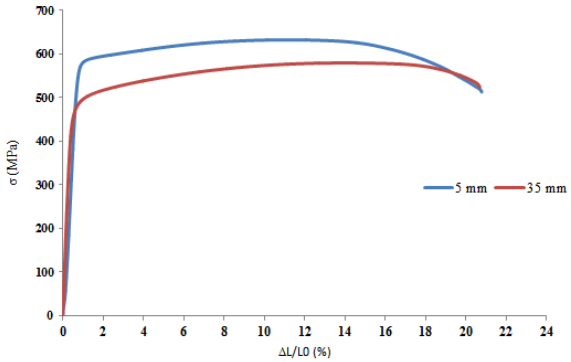

Fig. 5: Thickness effect on Cu-Ni-Si tensile behavior

In addition to the very remarkable tensile strength of 646 MPa improved by Silicon, the material has an failure strain of 21%, this ductility is due essentially to the high temperature of solution-quenching hardening

heat treatment. The progressive transition of the linear elasticity to the plastic deformation in the tensile curve requires the definition of the conventional yield strength $Re_{0.2\%}$ which is of the order of 567 MPa. From this stress value ($Re_{0.2\%}$), we appreciate a permanent strain that is small but measurable with precision, the behavior ceases to be elastic to become plastic.

Table: 1. Mechanical characteristics of Cu-Ni-Si

E (GPa)	$YS_{0.2\%}$ (MPa)	*UTS* (MPa)	*A* (%)	*υ*
123	**567**	**646**	**21.14**	**0.35**

Addition elements influence:

a) At the mechanical strength level:

Cu-Ni-Si exhibited excellent mechanical strength. The precipitation-hardened state gives it high mechanical properties. The addition of nickel and silicon leads to the formation of binary Ni_2Si compound, Ni_2Si improves the mechanical aspect by its dispersion in the matrix [9]. The Nickel element in copper presents, apart from the best corrosion resistance, an improvement of the affinity of the grains size in the matrix, which has the consequence of increasing the Cu-Ni-Si hardness and fostering the precipitation of the hardening phase during tempering heat treatment. Table 2 summarizes the effect of the addition elements on some Cu-Ni-Si mechanical characteristics.

Table: 2. Addition elements influence on the mechanical properties

	Tensile strength	Yield stress	Wear resistance	Failurestra in
Nickel	+	+	+	−
Silicon	+	+	+	

b) At the electrical conductivity level

The solubility of the intermetallic compound Ni2Si in the copper matrix limits the electrical conductivity of Cu-Ni-Si, it corresponds to a maximum of 9% at 1030 ° C, whereas at 650 ° C it comes down to1%. However, the Ni_2Si compound solubility is not negligible at conventional tempering temperatures (425 to 500 ° C); It is therefore rare that the electrical conductivity exceeds 38 to 45% IACS. The electrical conductivity increases linearly in Nickel and / or Silicon cuprous as their concentration decreases. Silicon is a disruptive element of electrical properties, thus requiring a very low content.

Fatigue behavior

a) S-N curves

There are various expressions which have been proposed to describe analytically the S-N curve. In order to present the evolution of the stress in function of the cycle number during a cyclic loading, these expressions must take account of the Wohler curve real shape, that is to say, of the two essential parts of this curve, the linear part representative of the limited endurance domain and the asymptotic part for the unlimited endurance domain. However, none of these expressions has a truly general character.

- ✓ The oldest proposition is that of Wohler :
$$\sigma = a - b \log N \quad (1)$$
- ✓ As early as 1910, Basquin proposed the formula :
$$\log N = a - b \log \sigma \quad (2)$$
- ✓ From 1914, Stromeyer introduced the equation:
$$\log N = a - b \log(\sigma - \sigma_D) \quad (3)$$

Where N is the number of cycles to failure, and σ the applied stress; a and b two material characteristics determined from two points of the experimental S-N curve.

The Stromeyer equation gives a much more realistic representation than Wohler and Basquin. The Wohler model gives a good representation of the mean part of the S-N curve, while the upper part (oligocyclic domain) is well estimated by the Basquin equation. The Stromeyer model seems closest to estimating the lifetime of Cu-Ni-Si. Although many models introduced on experimental bases exist, there is not at present a mathematical model well adjusted to the fatigue curve on these different parts.

In Fig.6, for each model, we distinguish the oligocyclic part which corresponds to highest level stress where the number of cycles to failure extends to 10^5. In this area we observe very quickly an important plastic strain followed by a specimen failure. The specimen reached generally a plastic accommodation state. For a cycle number compromised approximately between 10^5 and 10^7, in this domain, the response of the specimen is made in an elastic regime; the failure is not accompanied by a measurable plastic strain.

Elastic adaptation is a state when the specimen response becomes purely elastic; it is the limited endurance area in which most structures work. Around 10^7, the S-N curve presents a significant slope change for the Stromeyer and Basquin models, followed by a bearing where the curve tends towards a limit in parallel to the N axis. Cu-Ni-Si is estimated endure at 210 MPa.

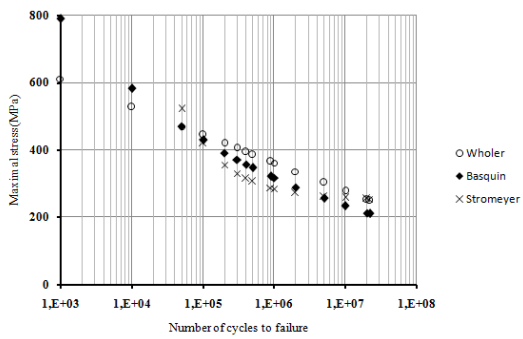

Fig.6: Comparison between Cu-Ni-Si S-N curves with different models

a) Fracture surface

Fig.7 shows the fracture surface of a sample which broke after 2.10^4 cycles. The fracture surface consists of three regions associated with crack initiation, crack growth and final fracture. The ZA area shows the initiation and the slow crack growth of one or a few loading cycles.

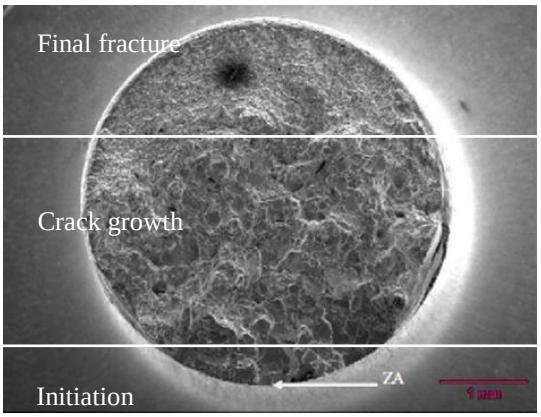

Fig.6: Fracture plan of fatigue sample

Conclusion:

In this study, the mechanical behavior of the precipitation-hardened Cu-Ni-Si alloy was highlighted, several properties have been identified. The material shows good mechanical resistance in monotonic tensile independently to the cutting direction. Mechanical behavior develops due to the intermetallic compounds precipitation during tempering heat treatment. In cyclical behavior, the Stromeyer mathematical model seems the most realistic to describe the fatigue behavior of Cu-Ni-Si. The material exhibits good endurance with a fatigue limit of 210 MPa.

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