Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 9 (2018) 186–198

Structural Integrity Procedia

www.elsevier.com/locate/procedia

IGF Workshop "Fracture and Structural Integrity"

Failure analysis and damage modeling of precipitate strengthened Cu–Ni–Si alloy under fatigue loading

Bouchra Saadouki[a]*, Thaneshan Sapanathan[b, c], Philipe Pelca[d], Mohamed Elghorba[a] and Mohamed Rachik[b]

[a]*Laboratoire de contrôle et de caractérisation mécanique des matériaux et des structures (LCCMMS), ENSEM, Casablanca, Morocco*

[b]*Sorbonne Universités, Université de Technologie de Compiègne, Laboratoire Roberval, CNRS UMR - 7337, Centre de Recherche Royallieu, CS 60319, 60203 Compiègne Cedex, France*

[c]*Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

[d]*Lebronzealloys – Bornel, 11 rue Ménillet, 60540 Bornel, France*

Abstract

Failure analysis and damage evolution in precipitation hardened Cu-2.5Ni-0.6Si alloy are investigated in this study. Firstly, experimental fatigue tests were performed to determine the S-N curve of the material. Then, based on the results of fatigue tests, we have modeled the damage using four linear and cumulative models. The intersection of damage-reliability curves allowed to define three stages of damage during the life cycle for various loading levels. The life fraction β_p reveals the stage of slow crack propagation where a preventive action must be adopted to ensure the proper functioning of the structure. The life fraction βc corresponds to the stage of sudden crack propagation when the damage becomes uncontrollable.

Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.

Keywords: *Cu-Ni-Si alloy, fatigue, loading levels, cumulative damage, life fraction.*

* Corresponding author. Tel.: +212-65-975-0455
E-mail address: bouchra.saadouki@gmail.com

2452-3216 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.
10.1016/j.prostr.2018.06.029

1. Introduction

Cu-Ni-Si alloys are often used in electronic, electrical and electromagnetic applications. Generally, they contain 1.4 to 3.8% of Ni and 0.2 to 1.8% of Si. These alloys are often strengthened by the precipitation hardening of the Ni_2Si phase. Fujiwaraet al. (1998) stated that sometime, other kinds of precipitates such as Ni_3Si and Ni_5Si_2 are also found in some Cu-Ni-Si alloys. Thus, Hornborgen (2001) found that structural hardening using a heat treatment process improves the mechanical properties of the base metal where tempering contributes significantly in the strengthening mechanism. In the case of Cu-Ni-Si alloys, Ageladarakis et al. (1999), Cheng et al. (2003), showed that the temperature and time of tempering directly influence the size and density of the precipitates. The maximum mechanical strength corresponds to an optimum size of the precipitates distributed within the copper matrix. As outlined by Lockyer et al. (1999), the effect of the particles'size and the fraction of precipitates determine the type of hardening mechanism and its amplitude.

Several research studies investigated the mechanical behavior of Cu-Ni-Si alloys and the influence of heat treatment on the microstructural evolution (Suzuki 2006, Monzen 2008 and Xie 2009). Recently, Cu-Ni-Si alloy becomes a promising candidate since they offer sufficiently high mechanical strength and good electrical and thermal conductivities. However, Saadouki at al. (2018) found that a periodic passage of very high frequency current in Cu-Ni-Si alloys generates a cyclic stress and eventually it leads to fatigue damage. Indeed, barely limited literature is available on the subject of fatigue behavior of the Cu-Ni-Si alloys. Sun et al. (2011) studied the influence of temperature and load ratio on the fatigue behavior of Cu-2.16Ni-0.72Si alloy and revealed that the phenomenon of dynamic embrittlement is responsible for the failure originated by an intergranular cracking. Goto et al. (2016) performed fatigue tests on a Cu-6Ni-1.5Si alloy to evaluate the role of microstructure in the initiation and propagation of fatigue cracks. They identified that the cracks begin in the grain boundaries and propagate along the crystallographic slip planes in the adjacent grains. Delbove et al. (2016) investigated the stress response to cyclic strain of $CuNi_2Si$(CW111C) using three models of fatigue resistance; the approach of dissipated plastic energy and Manson-Coffin relation appeared to be the best criteria for quantifying the periodic plastic strain. Several models concerning the damage mechanics were also proposed in the literature to quantify the damage. Particularly, many research studies proposed to quantify the cumulative damage at controlled stress level (Miner 1945, Shanley 1948, Valluri 1965 and Dubuc 1971). However, the theories proposed to estimate the damage at controlled strain level have not been well developed (Saches 1960, Manson 1967 and Bui-Quoc 1977).

The aim of this work is to quantify the fatigue damage of a Cu-2.5Ni-0.6Si alloy and to investigate its process of mechanical degradation under fatigue loading using the cumulative damage approach. For this purpose, fatigue tests under constant amplitude were performed on cylindrical specimens of Cu-2.5Ni-0.6Si to evaluate the cyclic loading behavior. Damage evolution was investigated using four damage models; the first model is Miner's rule, which considers that the damages are additive and independents of loading history. The second model is residual damage model which has been adapted to this study using the ultimate residual stress in the material after the fatigue loading. The third method is the "unified theory" giving the damage for each loading level as a function of life fraction. The last model is based on the bilinear rule which gives the percentage occupied by the initiation and propagation stages of the crack as a function of the total lifetime for an applied stress. The obtained results are represented as superimposed curves of damage and reliability plots. This correlation provides better understanding to estimate critical life fractions βp and βc defined by three damage stages: initiation, rising and acceleration.

Nomenclature

A	strain at failure in percentage
D	damage is 0 for specimen without damage and 1 for a fractured specimen
E	young's modulus (GPa)
m	material parameter
n	number of applied cycles
N	number of cycles to failure or total lifetime
N_a	number of cycle at crack initiation
N_p	number of cycle at start of crack propagation

UTS	ultimate tensile strength (MPa)
R	reliability
X	physical or mechanical parameter of the material which variations are caused by damage
X_0	value of X in the initial undamaged state
X_f	value of X in damaged state
$YS_{0,2\%}$	conventional yield strength at 0,2 % of strain
σ_a	critical ultimate residual stress at failure for $\beta = 1$ (MPa)
σ_D	material's endurance limit (MPa)
σ_e	critical endurance limit at failure for $\beta = 1$ (MPa)
σ_u	ultimate stress: UTS (MPa)
σ_{ur}	ultimate residual stress (MPa)
$\Delta\sigma$	stress variation during fatigue tests (MPa)
β	life fraction ,$\beta = n/N$
β_p	life fraction at slow crack propagation
β_c	critical life fraction at sudden crack propagation
γ	$\gamma = {}^{\Delta\sigma}/_{\sigma_D}$: nondimensional level stress indicating loading level
γ_u	$\gamma_u = {}^{\sigma_u}/_{\sigma_D}$: nondimensional ultimate stress
υ	poisson's ratio

2. Numerical models

Four models are used to predict the lifetime using cumulative damage at controlled stress level for Cu-2.5Ni-0.6Si alloy. They are (1) Miner's model, (2) residual damage model, (3) unified theory and (4) bilinear model. The simplest and most known approach is the linear rule of damage highlighted by Miner (1945).Residual damage model considers the variation of an intrinsic material parameter "X" which mainly depends on the damage evolution described by Montheillet et al. (2017).The unified theory has been proposed to combine the concept introduced by the nonlinear damage laws (Shanley 1948, Valluri 1965 and Dubuc 1971).The bilinear model gives the lifetime estimation in crack initiation and propagation based on the number of cycles to failure was founded by Grover (1960).

The first three models describe the damage progression as a function of life fraction β. The parameter β is given by the number of applied cycles divided by the number of cycles to failure. The bilinear model predicts lifetime at crack initiation and propagation (i.e. respectively the number of cycles necessary to initiate a crack and the number of cycles required to trigger its propagation) as a function of applied load level. For nonlinear models (e.g. residual damage and unified theory) which consider the loading history and describe the damage as a function of life fraction for different loads, while the loading levels can vary between a maximum stress value corresponds to the shortest service life and a minimum stress value leads to an unlimited service life.

The increase in damage is accompanied by the decrease in the reliability. To measure the reliability, we used the survival function, R(β), derived from the probability that corresponds to the Cu-2.5Ni-0.6Si alloy which has no failure for a lifetime β. The interest of expressing the reliability as a function of damage requires to identify the critical service life, which is an important information for preventive maintenance to avoid catastrophic failure of materials.

3. Theoretical descriptions of the numerical models

Miner suggests that the characteristic quantity of the work absorbed by the material is directly responsible for the degradation of the strength. The damage, DM, in constant amplitude is given by the following equation:

$$D_M = \beta = {}^{n}\!/_{N} \tag{1}$$

Failure is assumed to occur when the sum of damage is equal to one (Eq.2), which is not always verified. This rule assumes that the damage is independent of the loading levels and their order of application (loading history). However, the experimental results show that the order of application is an important factor in the computation of life fractions. Despite the presence of drawbacks in this model, Miner's law has had been widely considered to compute the damage because of its simplicity.

$$D_M = \sum_{i=0}^{k} \beta_i \tag{2}$$

Several works were then developed to remedy the problem posed by Miner's rule. The unified theory was established based on the continuity of many studies performed on the nonlinear laws of cumulative damage by Shanley (1948), Saches et al. (1960), Manson et al. (1967) and Bui-Quoc et al. (1977). Unified theory is based on damage quantification based on the reduction of material endurance limit. That is, the residual endurance limit as intrinsic characteristics of the material is influenced when a specimen is loaded with fatigue loading for a few cycles without failure.

According to the unified theory, the variation of damage D_{UT} as a function of life fraction β is defined by:

$$D_{UT} = \frac{\beta}{\beta + (1-\beta)\left[\dfrac{\gamma - (\gamma/\gamma_u)^m}{\gamma - 1}\right]} \tag{3}$$

Where, m is a parameter of material. For aluminum alloys and mild steel, m = 8 based on experimental characterizations investigated by Bathias et al. (1980). We also take m = 8 in this study.

Residual damage model quantifies the damage process in the evolution of a physical or mechanical material parameter "X" (e.g. density, area, Young's modulus, mechanical stress, etc). Residual damage DR, comprised between 0 and 1, is defined by the following expression:

$$D_R = \frac{X_0 - X}{X_0 - X_f} \tag{4}$$

In our study, parameter "X" is the residual stress. Residual strength loss due to the cyclic loading is considered as a macroscopic sign of degradation or activation of damage mechanism (at the microscopic scale) in each specimen. Another model in the literature couples the damage with the residual strength (Lemaitre 1996). The expression of damage coupled to ultimate residual strength (also called ultimate residual damage DUR) is defined by Eq.5:

$$D_{UR} = \frac{1 - \sigma_{ur}/\sigma_u}{1 - \sigma_a/\sigma_u} \tag{5}$$

Reliability varies inversely to the damage. Intuitively, it provides the following correlation between these two parameters:

$$R(\beta)+D(\beta)=1 \tag{6}$$

According to the bilinear rule, Grover (1960) suggested the concept of dividing material lifetime into two stages, such as:

$$N = N_a + N_p \tag{7}$$

The empirical relation used to quantify Na and Np is given by:

$$N_a = N - 14N^{0.6} \tag{8}$$

4. Implementation of the numerical models to the experimental case study

Firstly, the Cu-Ni-Si response under monotonic loading was investigated using tensile tests. Five flat specimens for each direction (longitudinal and perpendicular) were tested to ensure the reproducibility and the isotropy of Cu-Ni-Si alloy. The obtained mechanical properties of Cu-Ni-Si alloy are reported in Table 1.

Table-1.Monotonic tensile characteristics of the Cu-Ni-Si alloy

E (GPa)	$YS_{0.2\%}$ (MPa)	*UTS* (MPa)	*A* (%)	υ
123	567	615	21.14	0.34

After that, fatigue tests were performed to estimate the load bearing capacity of the tested material under cyclical loading conditions. Lifetime of the specimen depends on both static part (mean stress) and dynamic part (amplitude of the stress variations). The fatigue tests were carried out on an MTS 810 biaxial hydraulic machine at an imposed stress and a temperature of 20 ° C. Solicitations were piloted in uniaxial cyclical mode, with a sinusoidal waveform. The tests launch requires the definition of the first value of imposed stress; this corresponds to the conventional yield strength. Thus, for each stress level, specimens fail after certain number of cycles called number of cycles to failure.

5. Results and discussions

Unified theory clearly reflects the nonlinearity of cumulative damage and considers the loading history. The damage variation as a function of life fraction is illustrated in Fig.1. For the same life fraction β, the value of the damage (DUT) increases with the increase in the applied loading level (γ increases). For loadings levels in low cycle fatigue and at the beginning of limited endurance fatigue domains in the S-N curve (four cases of 500 -360 MPa), damage curves become closer and regularly spaced. For these four cases, the progression of damage mechanism is slow.

For loadings levels in the end of limited endurance fatigue domain (300MPa and 260MPa), damage curves are at far from other cases. For life fractions (β) from 0 to 0.8 the damage process remains slow, and then it accelerates towards the end of material lifetime. That is, after the life fraction becomes 0.8, damage increases exponentially and reaches the value of D=1 at the complete failure. While, Miner model is independent of loading level and it overestimates the damage values compared to unified theory (Fig. 1).

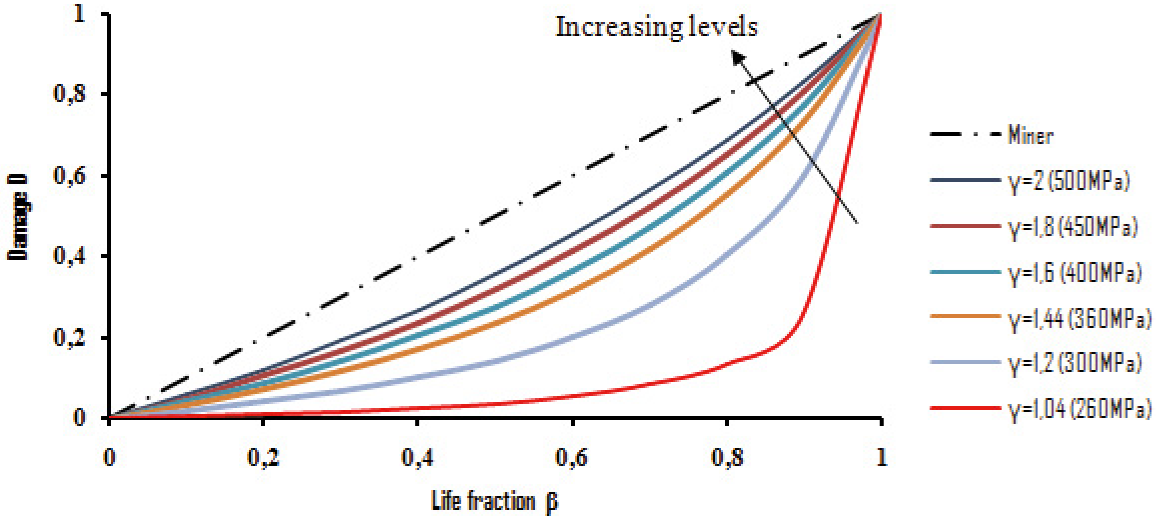


Fig. 1. Characteristic curves of the Cu-Ni-Si alloy representing the damage as a function of life fraction according to the unified theory for different loading levels and Miner model.

Unified theory is characterized by calculating the stress at which failure occurs under static tensile loading for a specimen that was already subjected to a certain life fraction β at a given stress level σ. This stress is called ultimate residual stress σ_{ur} given by Eq.9:

$$\frac{\sigma_{ur}}{\sigma_u} = \left[\gamma - \frac{1}{\frac{1-\beta}{\gamma-1} + \frac{\beta}{\gamma - \left(\gamma/\gamma_u\right)^m}} \right] \tag{9}$$

Fig.2 shows the variation of the nondimensionalized ratio between ultimate residual stress (σ_{ur}) and the ultimate tensile stress (UTS denoted by σ_u) as a function of life fraction for the highest investigated loading level of 500MPa ($\gamma = 2$) and the lowest loading level 260MPa ($\gamma = 1.04$). The decrease in the ultimate residual stress is noticed as a function of fraction life; this reflects the static strength loss gradually occurs as the life fraction increases (Fig. 2). It also indicates that the curve corresponds to $\gamma = 2$ is located below the curve of $\gamma = 1.04$. This verification is in good agreement, since a higher loading level leads to a decrease of the residual ultimate stress compared to a lower loading level.

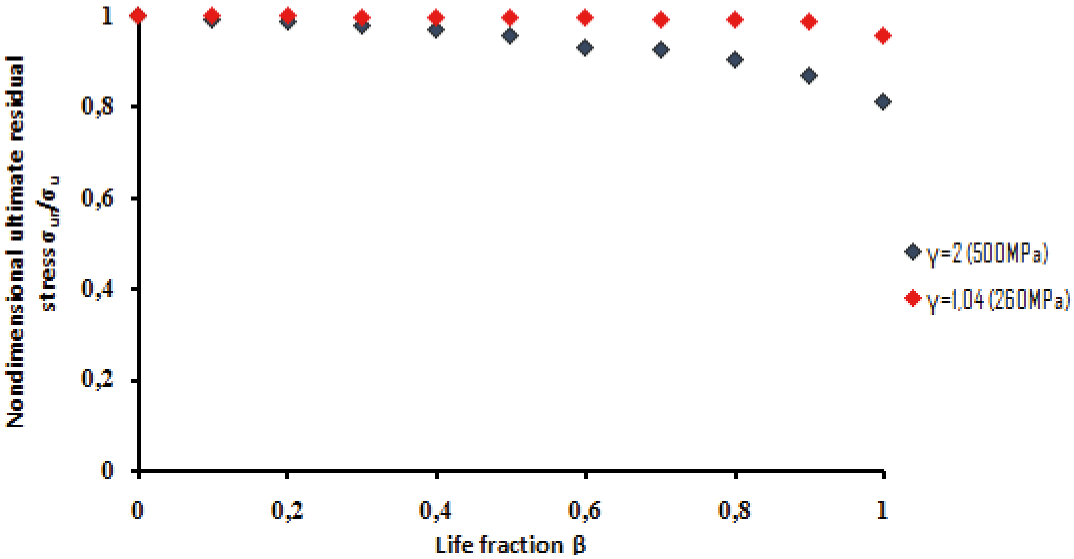


Fig. 2. Variation of nondimensionalized stress ratio as in function of life fraction for Cu-Ni-Si alloy according to the unified theory for the two extremes loading levels.

Unified theory defines the damage in terms of the two following criteria:

a) Loss of strength in static tensile

In its initial state, Cu-Ni-Si has the ultimate tensile stress σu = 615 MPa, then this strength decreases gradually as the number of loading cycles in fatigue increases until failure . In a case of when fatigue test is interrupted before the final failure and the specimen is then tested with a uniaxial tensile loading, failure occurs at a stress level of σur. The σur lies in between σu and σ_a (critical ultimate residual stress).

b) Reduction of endurance limit

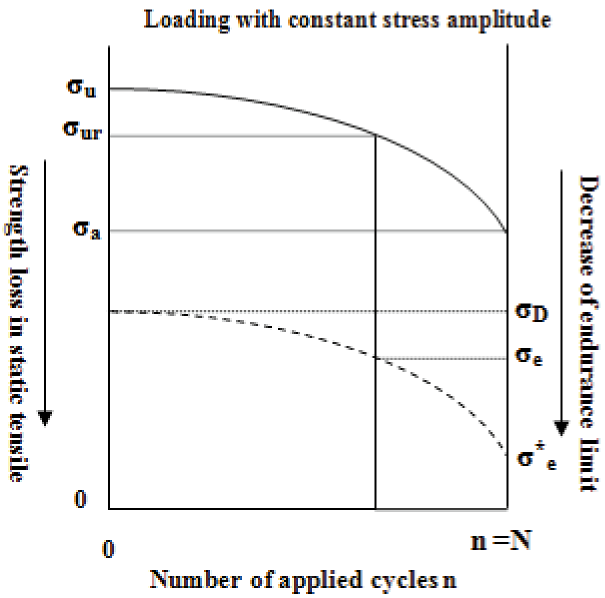
Cu-Ni-Si has the endurance limit σ_D = 250 MPa in its undamaged state, this limit decreases when the number of applied cycles increases, it takes a critical value σe.

Fig.3 show a general illustration (a) as well as a special case (b) for γ = 2 (equivalent to 500MPa loading level) of strength loss in static tensile and reduction of endurance limit for the Cu-Ni-Si during a fatigue solicitation.

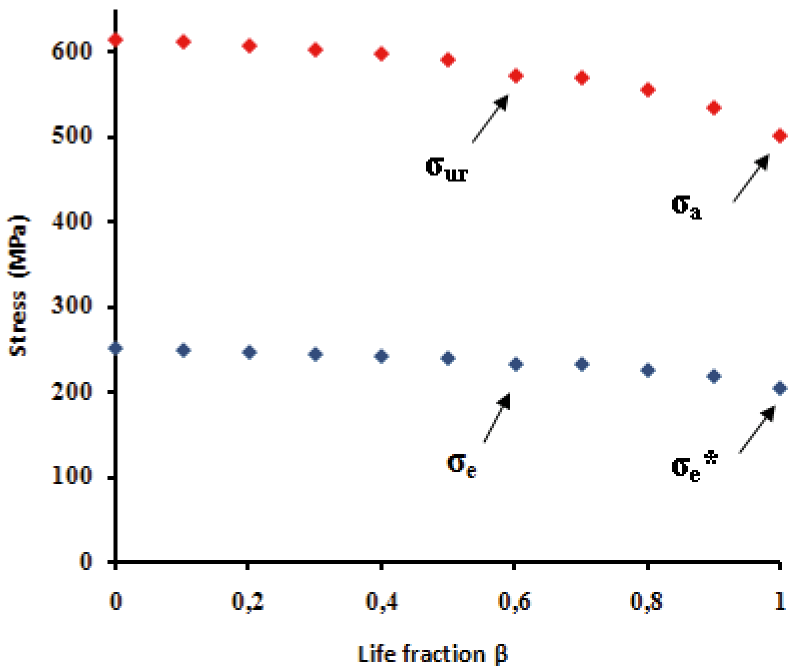
The variation of damage as a function of life fraction according to residual damage model is illustrated in Fig.4. The increase in damage corresponds to the loss of strength for cuprous samples; this loss evolves when life fraction increases.

The comparison of the damage using unified theory and residual damage model for those two extreme loading cases is illustrated in Fig.5. A difference between the damage predictions is distinguishable for the residual damage model and unified theory for loading level corresponds to 500 MPa. This difference is less noticeable for 260 MPa loading level.

Damage represents two aspects, namely the physical aspect related to mechanic of crack and descriptive aspect necessary to evaluate damage level in industry. Unified theory and residual damage model have developed to estimate the physical aspect of Cu-Ni-Si alloy damage, this aspect corresponds to variations of ultimate residual stress as a mechanical property. These variations reflect the consequence on the structural modifications under the repeated loading and depend directly on the propagation of the cracks. Crack propagation induces the decrease of residual strength in the subsequent applied cycle. The descriptive aspect consists of the quantitative representation of Cu-Ni-Si endurance subjected to stress histories. Being a time function, the evolution of fatigue damage must be intended to ensure structure integrity. This endurance is estimated from the correlation between the damage and reliability.



(a)



(b)

Fig. 3. Schematic representation of the strength loss in uniaxial tensile test and reduction of endurance limit during fatigue test (a) general illustration (b) Cu-Ni-Si at $\gamma = 2$

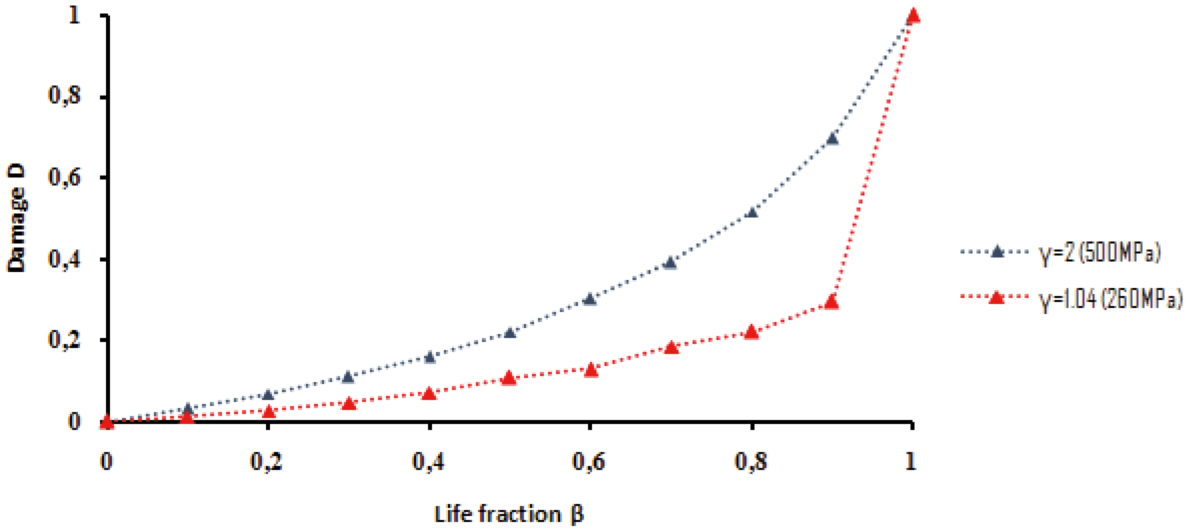


Fig. 4. Characteristic curves of the Cu-Ni-Si representing damage in function of life fraction according to residual damage model for the two extremes loading levels

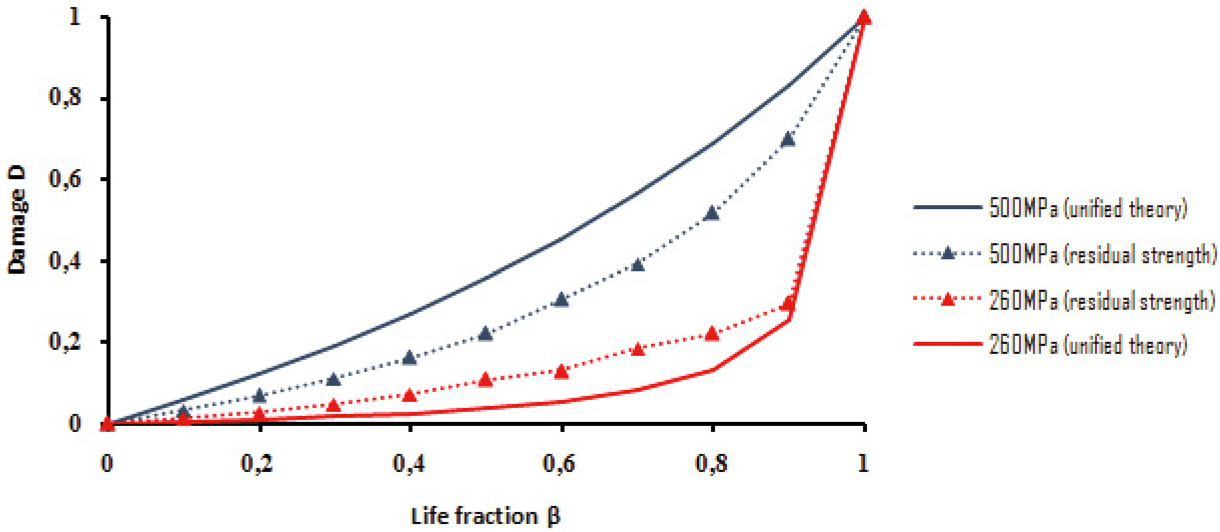


Fig. 5. Comparison of damage prediction from the unified theory and residual damage model for the two extremes loading levels.

The failure-reliability relation enables to optimize the Cu-Ni-Si use and to characterize its mechanical behavior at various life fractions. To measure its reliability, we used the survival function R (β), corresponds to the probability of the Cu-Ni-Si has no failure at the life fraction β. In particular, the advantage of determining the correlation between damage and reliability facilitates to identify the corresponding life fraction where the damage becomes critical.

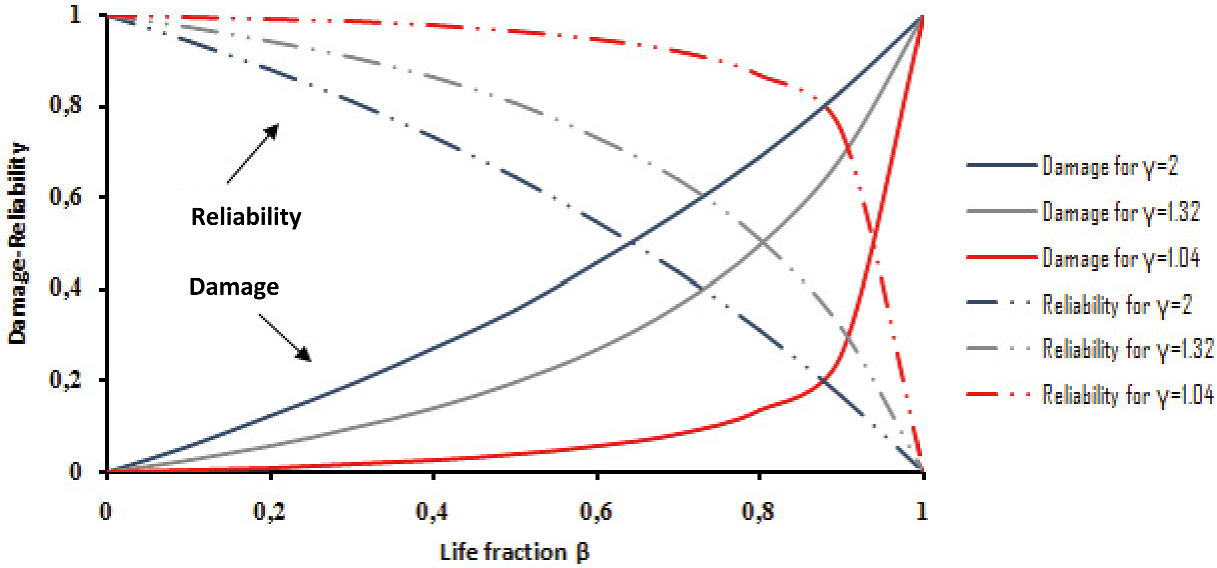


Fig. 6. Superposition of damage according to unified theory and reliability curves for Cu-Ni-Si alloy for the extremes and average loading levels.

Cu-Ni-Si alloy damage has a crack initiation stage, followed by a crack growth leading finally to failure. It is generally difficult to define the transition points between these two stage since the visible follow of cracks is delicate, we then refer to the criterion of reliability to define the three life stages of Cu-Ni-Si alloy for a given stress level γ. We define that the material is in the initiation stage of the damage when its reliability ≥50%. Below 50% of reliability and above 10%, the damage propagates slowly, and as soon as reliability reaches the threshold of 10%, a sudden damage propagation is predicted.

For γ = 2, the slow propagation stage starts from the life fraction βp = 0.63 and ends at the critical life fraction βc = 0.95 that marks the beginning of sudden propagation. In other words, for a Cu-Ni-Si structure subjected to cyclic loading of 500 MPa, fatigue cracks begin to grow from 13751 cycles. Then damage propagates further in the material up to a number of cycles of 20736 where the propagation becomes rapid and the rupture finally occurs at 21828 cycles.

For a less constraining loading where γ = 1.32, equivalent to an applied stress of 330 MPa, damage is initiated from the beginning of material life up to 443664 corresponding to a life fraction βp = 0.8, then damage becomes uncontrollable since a life fraction of βc = 0.97 equivalent to 537942 before total damage at 554580.

At γ = 1.04 loading, the same damage scenario is repeated but with a very optimal reliability as the material is loaded at 260 MPa, loading higher at only 4% than the endurance limit. It is a very suitable loading level for a Cu-Ni-Si structure to have a very long lifetime. In this case, damage initiation dominates the material's lifetime and spreads out up to βp = 0.95 (5278013 cycles). Slow propagation stage is very narrow, Cu-Ni-Si indicates a sudden propagation from βc = 0.99 equivalent to 5500245 cycles, while failure occurs after a few cycles.

For the three loading levels, the initiation stage occupies the largest part of the material's lifetime, which is common for structures loaded in fatigue. However, the time taken by this stage differs depending on the loading level; it occupies respectively 63%, 80% and 95% of the Cu-Ni-Si lifetime for the loadings of 500 MPa, 330 MPa and 260 MPa, respectively.

At 260 MPa loading, the Cu-Ni-Si behavior seemed to be the least constraining since the cracks began to propagate only from 95% of the total material lifetime. However, the slow propagation is very small (4% of the lifetime) and suddenly it turns into a rapid propagation (1% of the lifetime).Therefore, for this loading level, and after a crack initiation, a very strict follow must be applied to prevent failure that occurs brutally in a very limited time interval.

The bilinear model also confirms the conclusions obtained from the damage-reliability on the various life stages of Cu-Ni-Si alloy over its total lifetime. Fig.7 shows the predictions of Cu-Ni-Si alloy's S-N curve with separate crack initiation stage Na and crack propagation stage Np. However, the magnitudes of Na and Np do not necessarily represent the physical stages corresponding to the initiation and propagation of cracks due to fatigue loading. The variation of Na / N ratio as a function of the total lifetime is shown in Fig.8. These results represent the percentage occupied by the crack initiation phase over the total lifetime of the Cu-Ni-Si alloy. They indicate that crack initiation phase represents a significant proportion of lifetime on both fatigue limited and fatigue unlimited endurance domains. Indeed, the application of cyclical loading close to the endurance limit leads to a lifetime which initiation occupies more than 98%. After a certain number of cycles, in some grains, slip bands were observed on fracture surfaces (Fig.9). Louat et al. (1956) stated that these bands have often been observed in copper; they lead to the appearance of microcracks by the intrusion-extrusion mechanism.

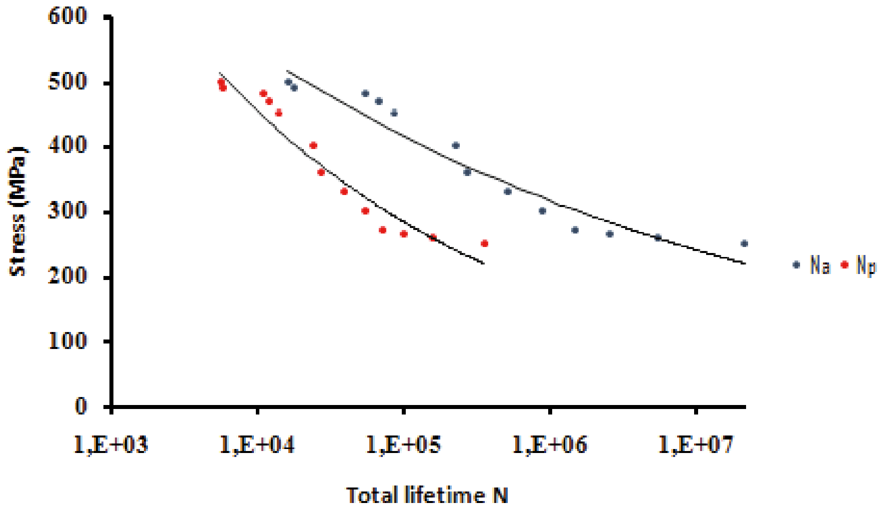


Fig. 7. Predictions of stress against total lifetime giving the lifetime at crack initiation N_a and crack propagation N_p for the Cu-Ni-Si alloy according to bilinear model.

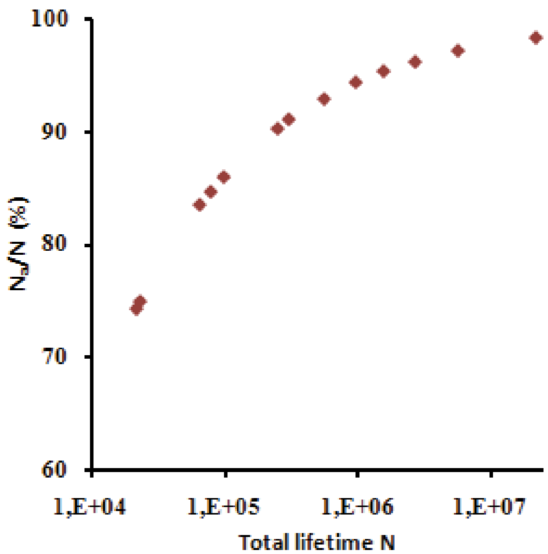


Fig. 8. Percentage of lifetime corresponds to the crack initiation stage as a function of total lifetime for the Cu-Ni-Si alloy under fatigue loading.

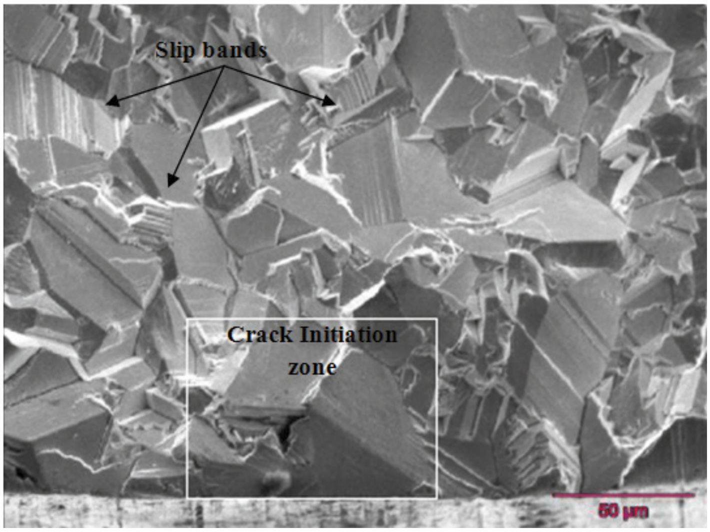


Fig. 9. Scanning electron microscopy observation showing the slip bands on the fracture surface of Cu-Ni-Si alloy loaded with the cyclic loading of 260 MPa.

6. Conclusions

Fatigue damage behavior of a Cu-2.5Ni-0.6Si alloy hardened by the precipitation of the Ni2Si phase is investigated in this paper. Fatigue tests with constant stress amplitude were performed on cylindrical specimens followed by the analysis of the degradation process and material failure using four different damage models. Miner's linear approach is not suitable to predict the damage behavior since it does not represent the actual damage. Unified theory and residual damage model have well described the fatigue damage phenomenon. The advantage of unified theory is that for a structure subjected to fatigue; after certain cycles, it is easy to define the new values of the residual stress and endurance limit.

Three life stages of Cu-2.5Ni-0.6Si were determined by coupling the damage and reliability behavior of the material. Under the fatigue loading of a Cu-Ni-Si structure, damage must be controlled from the beginning of the slow crack propagation stage where reliability falls to 50%. However, this damage becomes critical as soon as reliability reaches to 10%. The intersection of damage-reliability curves allowed us to determine the critical life fractions βc indicating the critical number of cycles or the critical time when a preventive action must be taken. The Life fraction at slow crack propagation (βp) depends on the loading level and increases with the decrease of loading level, and it gives the values of 0.63, 0.8 and 0.95 for the loads 500MPa, 330MPa and 260MPa, respectively. This result is crucial for preventive maintenance, to intervene at the appropriate time to change the damaged part.

The bilinear model is also in good agreement with the results of the damage-reliability curves for loading levels 330MPa and 260MPa. The bilinear model predictions indicates that the crack initiation stage dominates the lifetime of Cu-Ni-Si in fatigue limited and unlimited endurance domains and occupies up to 99% of the total lifetime.

Acknowledgements

Authors acknowledge the funding of COILTIM project from “Région Picardie” and “Le fonds européen de développement économique et régional (FEDER)”.

References

Fujiwara, H., Sato, T., Kamio, A., 1998. Effect of alloy composition on precipitation behavior in Cu-Ni-Si alloys. Journal of the Japan Institute of Metals, 62(4), 301-309.

Hornborgen, E., 2001. Hundred years of precipitation hardening, Journal of Light Metals, 1.

Cheng, J., Wang, M., 2003. Thermomechanical treatment of Cu-1.5Ni-0.27Si alloy. Chinese Journal of Non-Ferrous Metals, 13(5), 1061-1065.

Ageladarakis, PA., O'Dowd, NP., Webster, GA., 1999. Tensile and Fracture Toughness Tests of CuNiSi at Room and Cryogenic Temperatures. JET–R 01; 18 p; Available from British Library Document Supply Centre.

Lockyer, SA., Noble, FW., 1999. Fatigue of precipitate strengthened Cu-Ni-Si alloy. Materials Science and Technology 15, 1147-1153.

Suzuki, S., Shibutani, N., Mimura, K., Isshiki, M., Waseda, Y., 2006. Improvement in strength and electrical conductivity of Cu–Ni–Si alloys by aging and cold rolling. Journal of Alloys and Compounds, 417, 116–120.

Monzen, R., Watanabe, C., 2008. Microstructure and mechanical properties of Cu–Ni–Si alloys. Materials Science and Engineering A, 483–484, 117–119.

Xie, H., Jia, L., Lu, Z., 2009. Microstructure and solidification behavior of Cu–Ni–Si alloys. Materials Characterization, 60, 114 – 118.

Saadouki, B., Sapanathan, T., Pelca, PH., Elghorba, M., Rachik, M, 2018. Fatigue damage in fieldshapers used during electromagnetic forming and welding processes at high frequency impulse current. International Journal of Fatigue, 109, 93-102.

Sun, Z., Laitem, C., Vincent, A., 2011. Dynamic embrittlementduring fatigue of a Cu–Ni–Si alloy. Mater SciEngA, 528, 6334-6337.

Goto, M., Han, SZ., Lim, SH., Kitamura, J., Fujimura, T., Ahn, JH., Yamamoto, T., Kim, S., Lee, J., 2016. Role of microstructure on initiation and propagation of fatigue cracksin precipitate strengthened Cu–Ni–Si alloy. International Journal of Fatigue, 87, 15-21.

Delbove, M., Vogt, JB., Bouquere, lJ., Soreau, T., Primaux, F., 2016. Low cycle fatigue behavior of a precipitation hardened Cu-Ni-Si alloy.International Journal of Fatigue, 92, p. 313–320.

Miner , MA., 1945. Cumulative damage in fatigue, journal of applied mechanics, Trans. ASME, 67, A159-A164.

Dubuc, J., Bui-Quoc, T., Bazergui, A., Biron, A., 1971. Unified theory of cumulative damage in metal fatigue. journal of basic engineering. Transactions of ASME, 691-698.

Valluri, FR., 1965. Journal of applied aerospace engineering, 20, . 68-89.

Shanley, FR., 1948. The column paradox, journal of aeronautical sciences. 13(12), 678.

Manson, S., Freche, J., Ensign, C., 1967. Application of a double linear damage rule to cumulative fatigue. ASTM STP 415, Fatigue Crack Propagation, 384-412.

Saches, G., Gerberich, WW., Weiss, V., Latorre, JV., 1960. Proc. ASTM. 60, 512-529.

Bui-Quoc, T., Biron, A., 1977. Order effect of strain applications in low cycle cumulative fatigue at high temperatures. Transactions of the international conference on structural mechanics in reactor technology, San Francisco, L 912, 1-10.

Montheillet, F., Briottet, L., 2017. Endommagement et ductilité en mise en forme. M3032 V1.

Grover, HJ., 1960. An observation concerning the cycle ratio in cumulative damage. Fatigue of Aircraft structures, ASTM STP 274, 120-124.

Bathias, C., Bailon, JP., 1980. La fatigue des matériaux et des structures, Collection Université De Compiègne, Maloine S.A. Editeur. Paris

Lemaitre, J., Chaboche, JL., 1996. Mécanique des Matériaux solides, Dunod, Paris, 2e édit.

Louat, N., Thompson, N., Warsworth, N., 1956. The origin of fatigue fracture in copper. Phil.Mag, 1, 113-126.