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Fuzzy Logic Prediction of Stress-Strain Behavior Parameters of Two-Phase Materials. Application to WC-Co System

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Abstract

This study is a further contribution to predict stress-strain behavior parameters such as the resistance of α phase and β phase as a function of α phase volume fraction. A Fuzzy Logic approach is developed to predict these mechanical parameters. A set of stress-strain experimental curves of WC-Co two-phase materials was used to predict the stress-strain parameters as a function of Co volume fractions. The calculated stress-strain curves are in good agreement with the evolution of the experimental ones. The resistance of phases increases with the rise of the WC volume fraction; this is due to hardening effect of phases in the two-phase material.

Keywords: Fuzzy Logic, Two-phase materials, Stress-strain, WC-Co

INTRODUCTION

The plastic behavior of two-phase materials is governed by the mechanical properties of each phase, volume fraction and morphological distribution of the second phase; these parameters must be introduced in a modeling procedure of deformation.

The theoretical treatments of the deformation behavior of two-phase materials suppose that the microstructure can be modeled as a composite material constituted of hard phase and soft phase. The difference between the different approaches results in the distribution of the deformation between the two phases, the manner that a phase affects the flow characteristics of the second one.

Different analytical models have been used to build the theoretical stress-strain curve of a two-phase material starting from its corresponding constituent single-phase materials: mixture laws (Mileiko., 1969; Araki et al., 1977), finite elements models (Durand et al., 1990; Durand et al., 1992) and self-consistent models (Berveiller et al., 1981; Durand et al., 1993). Recently, direct new methods such as genetic algorithms (Taouche et al., 2003) and artificial neural networks (Taouche., 2015) have been developed to optimize and predict the entire stress-strain curve of two-phase materials starting from numerical experimental data.
The fuzzy logic approach is a new method to predict the mechanical behavior of materials; it is actually little used in materials science field and there are no many studies were carried out in the field of mechanical behavior of two-phase materials (Ûnal et al., 2007; Güler et al., 2012; Dilmaç et al., 2013).

This study presents the results using Fuzzy Logic approach based on a Hollomon (Hollomon., 1945) type model based on an iso-strain condition and the stresses follow an exponential law with two parameters in each phase : the resistance and the adjustment parameters; and the stress is distributed in the two-phase material by the rule of mixtures.

THE WC-Co TWO-PHASE MATERIALS

The WC-Co two-phase materials are constituted morphologically of a hard phase of tungsten carbide WC with hexagonal structure and a soft metallic binder phase of Co with CFC structure (The Co has a hexagonal compact structure at ambient temperature and passes to CFC structure at 405°C) (Figure 1) (Poech et al., 1992).

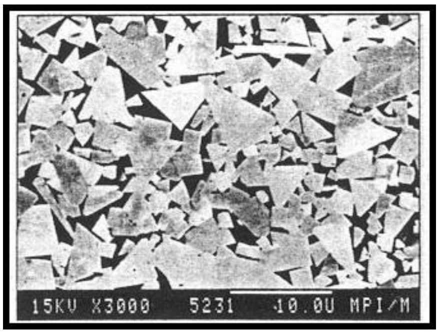

Figure.1: The microstructure of WC-9%wt Co material (Poech et al., 1992)

The mechanical properties of WC-Co materials depend essentially on their composition (volume fraction of Co) and their microstructure (particularly on the grains size of WC phase). In general, the diminution of the grains size of WC phase increases the mechanical properties of these materials such as the hardness, the resistance, the transverse fracture and the hardening. The WC has an elastic limit of 970 MPa, the Co has an elastic limit of 270 MPa (Poech et al., 1992). The elastic limit of the WC-Co two-phase materials depend on the grains size of WC phase and the volume fraction of the Co (Okamoto et al., 2005).

THE FUZZY LOGIC APPROACH

A general fuzzy inference system (FIS) has four steps: fuzzification, fuzzy rules, fuzzy output and defuzzification.
In this study, the Mamdani-type fuzzy inference was used (Figure 2), the volume fraction of Co is used as an input variable, the four parameters k_α and k_β, n_α and n_β are used as output variables.

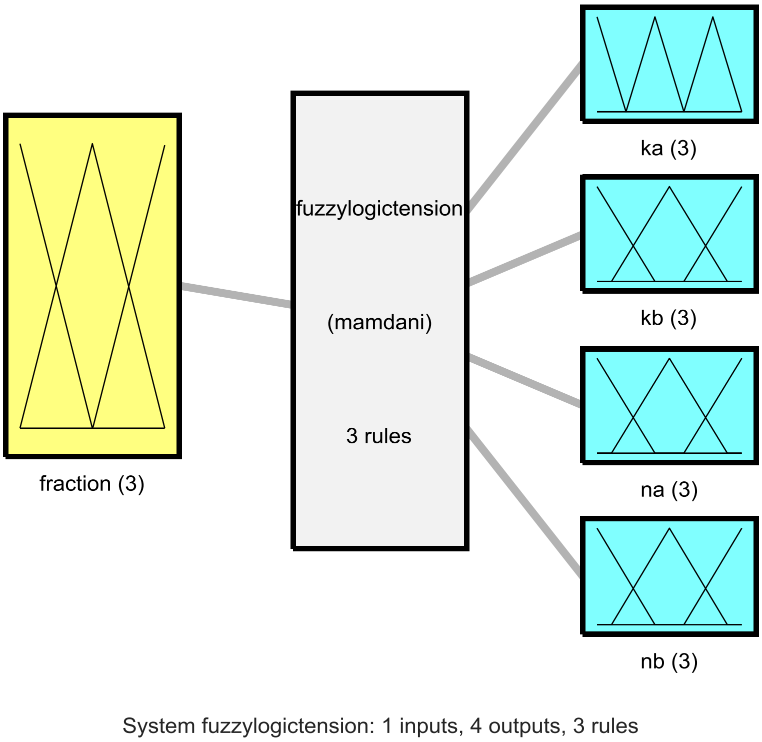

Figure.2: Fuzzy Inference System

The rules used in our study (in the cases of tension and compression) are the following:
R1: If (volume fraction ***is*** *f1*) ***then*** (resistance alpha ***is*** *kα1* ***and*** resistance beta ***is*** *kβ1*) ***and*** (adjustment parameter alpha ***is*** *nα1* ***and*** adjustment parameter beta ***is*** *nβ1*).
R2: If (volume fraction ***is*** *f2*) ***then*** (resistance alpha ***is*** *kα2* ***and*** resistance beta ***is*** *kβ2*) ***and*** (adjustment parameter alpha ***is*** *nα2* ***and*** adjustment parameter beta ***is*** *nβ2*).
R3: If (volume fraction ***is*** *f3*) ***then*** (resistance alpha ***is*** *kα3* ***and*** resistance beta ***is*** *kβ3*) ***and*** (adjustment parameter alpha ***is*** *nα3* ***and*** adjustment parameter beta ***is*** *nβ3*).
The membership functions are triangular ones for input and output variables, as shown in Figure 3.

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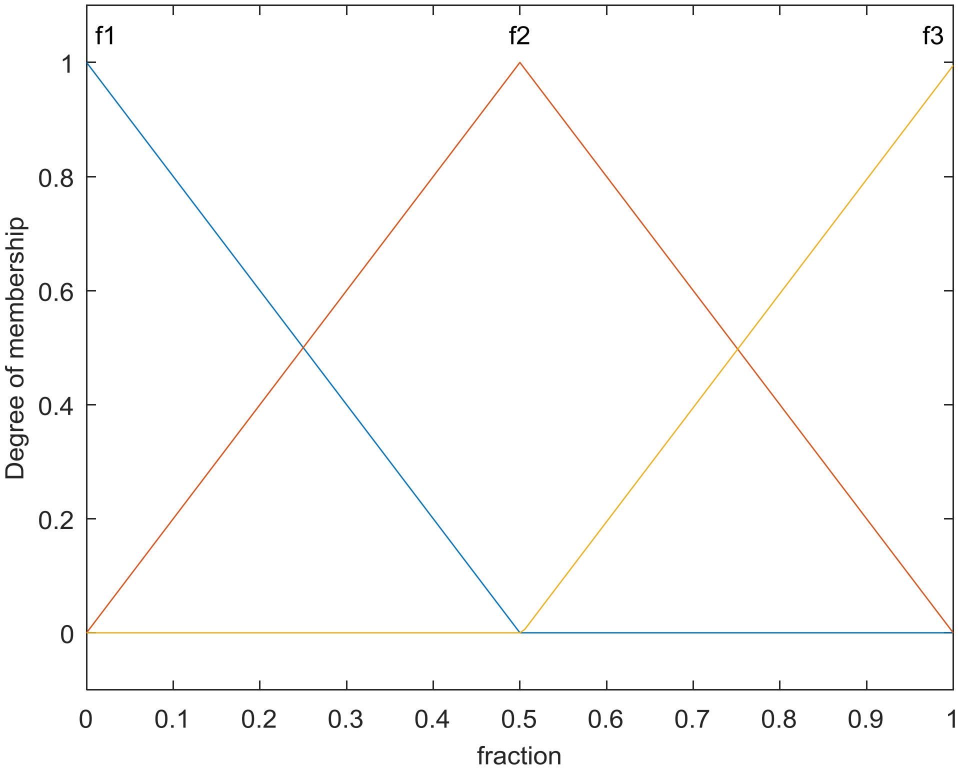

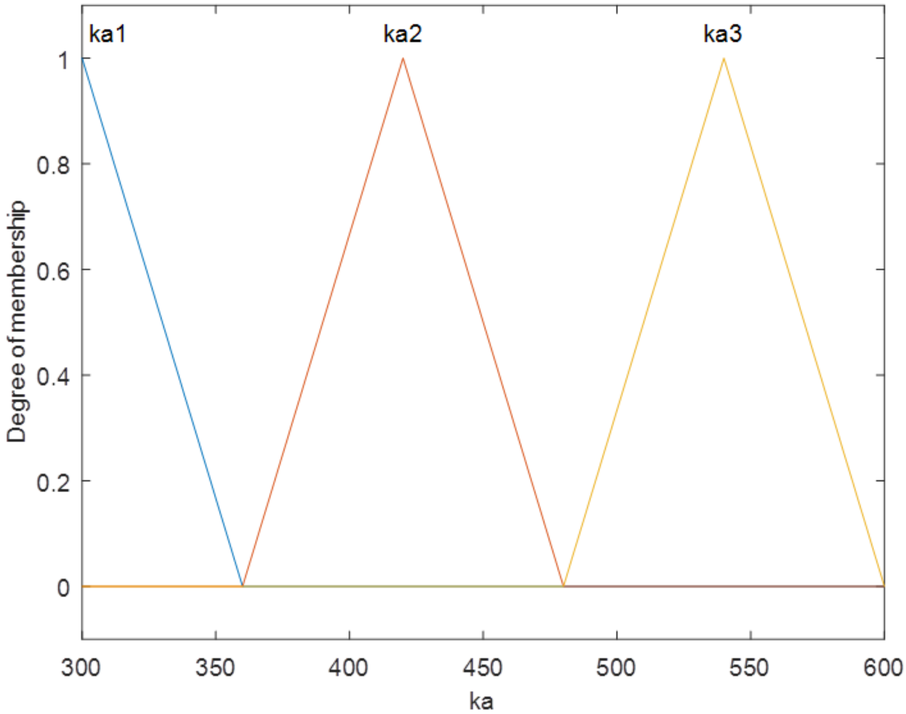

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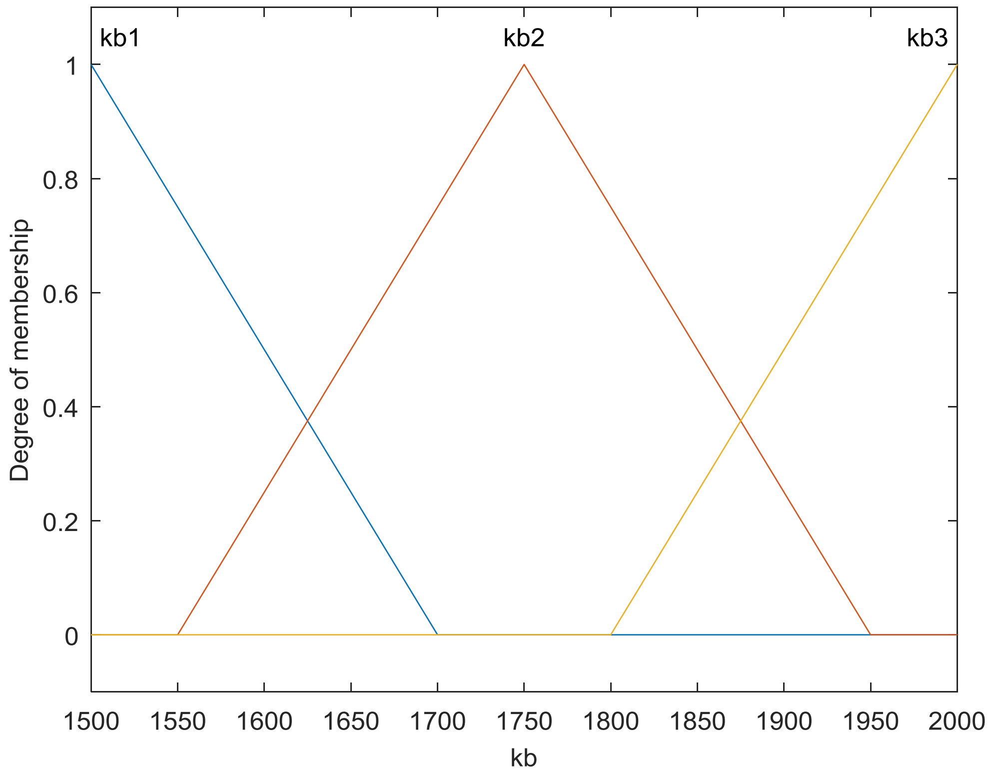

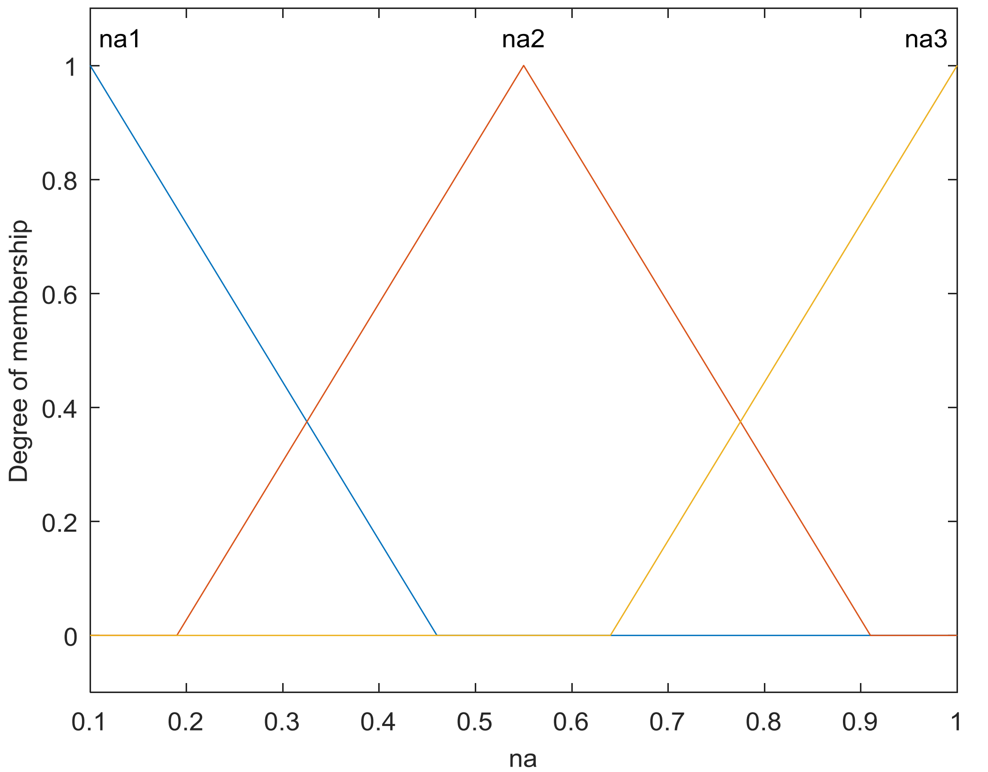

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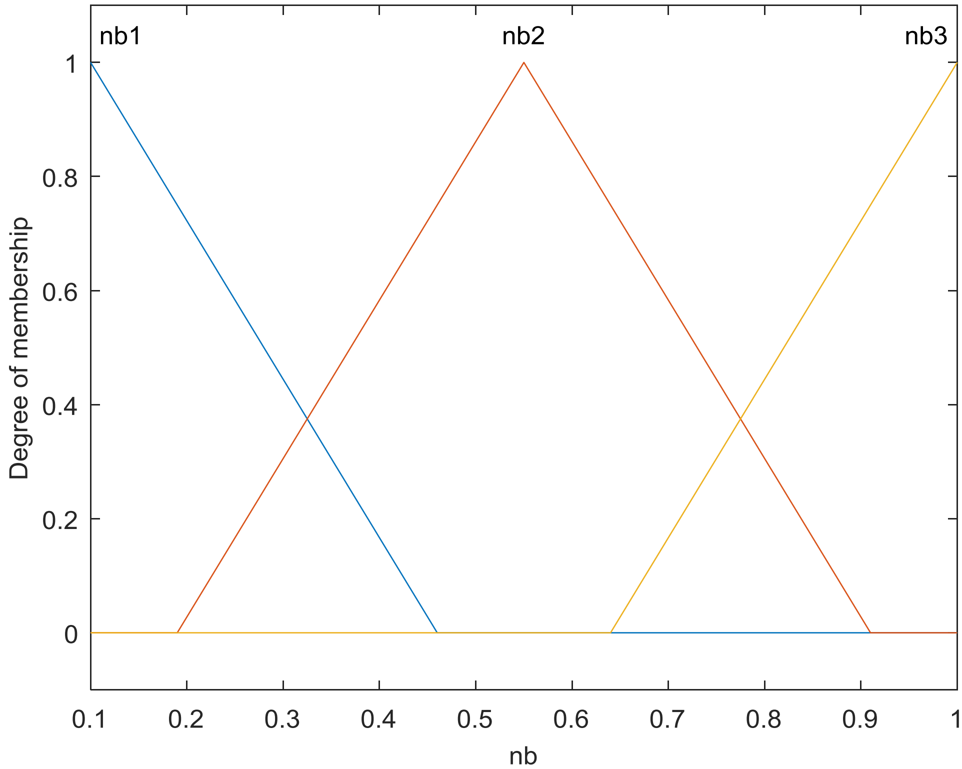

Figure.3: Membership functions for tension case

APPLICATION OF FUZZY LOGIC TO PREDICT STRESS6STRAIN PARAMETERS

T he model used in this study to predict the stress-strain behavior parameters is based on continuum mechanics notions, an iso-strain condition is imposed (Equation 1) and the stress is distributed following the rule of mixtures (Equation 2), an exponential Hollomon (Hollomon., 1945) form is applied to express the stress-strain relation of each phase (Equations 4 and 5).

$$\varepsilon = \varepsilon_\alpha = \varepsilon_\beta \quad (1)$$

where ε, ε_α, ε_β are strains of material, α phase and β phase respectively.

$$\sigma = f_\alpha \sigma_\alpha + f_\beta \sigma_\beta \quad (2)$$

where σ, σ_α, σ_β are stresses of material, α phase and β phase respectively.

with $$f_\alpha + f_\beta = 1 \quad (3)$$

where f_α and f_β are volume fractions of α phase and β phase.

$$\sigma_\alpha = k_\alpha (1 - \exp\left(-\frac{\varepsilon}{n_\alpha}\right)) \quad (4)$$

$$\sigma_\beta = k_\beta (1 - \exp\left(-\frac{\varepsilon}{n_\beta}\right)) \quad (5)$$

where k_α and k_β express the resistance of α phase and β phase in the two-phase material. Parameters n_α and n_β express the adjustment of α phase and β phase to the stress plateau appearance.

For k_α and k_β ranges are around the elastic limit of each phase that varies with the variation of the second phase volume fraction.

For n_α and n_β ranges are between 0.1 and 1.

RESULTS

The Fuzzy Logic toolbox of MATLAB is applied to predict the stress-strain curves of the WC-Co two-phase material deformed in tension (Nishimatsu et al., 1960) and compression (Doi et al., 1969).

WC-Co in tension

In the tension case of the deformed materials WC-Co, the volume fractions used in training procedure are 90%, 65% and 50% of Co.

The obtained parameters k_α, k_β and n_α, n_β are listed in the table (1).

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The comparison between calculated and experimental curves shows a good agreement between these curves (Figure 4), it shows that curves corresponding to the volume fractions 95%, 85%, 75% and 45% of Co integrate very well in the evolution of the experimental curves.

The variation of the resistances k_α and k_β is illustrated in Figure 5; it is linear variation in the range of [50% - 85%] of Co.

Table 1: Parameter values obtained by Fuzzy Logic prediction. WC-Co system in tension

The volume fraction of Co (%)	K_α (MPa)	K_β (MPa)	n_α	n_β
95	373.6	1853.9	0.2	0.9
85	482.8	2295.0	0.2	0.8
75	522.7	2538.9	0.2	0.8
45	674.3	3781.1	0.3	0.7

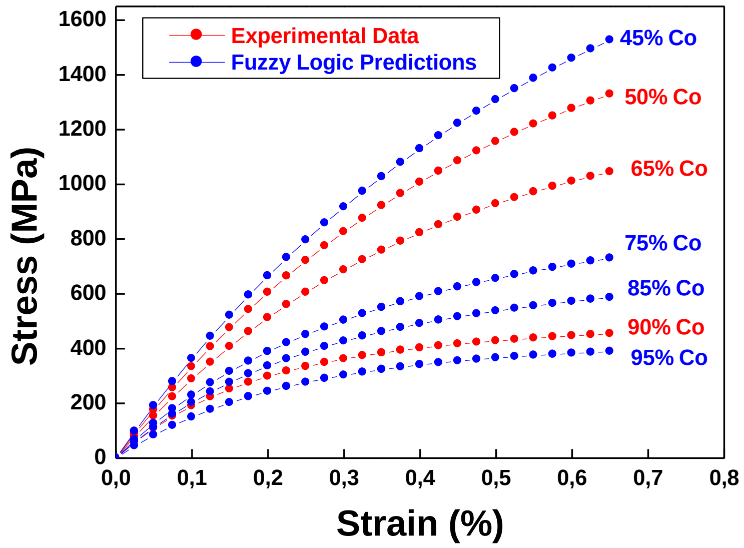

Figure.4: Predicted stress-strain curves. WC-Co system in tension (experimental data (Nishimatsu et al., 1960)

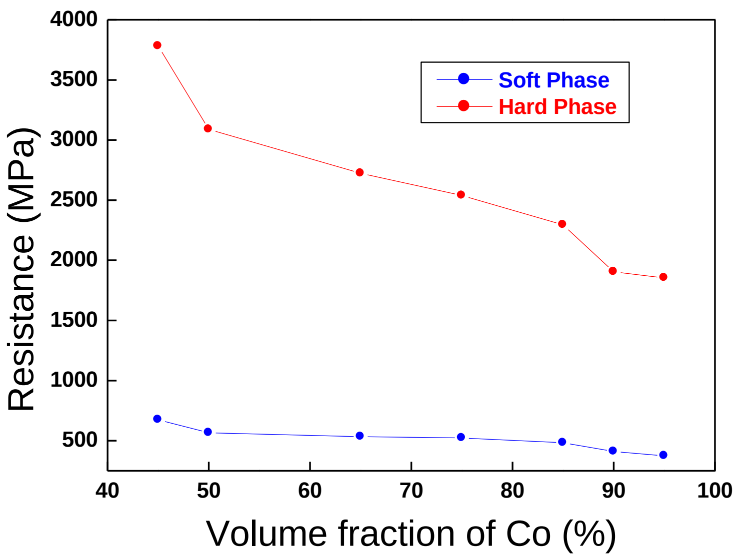

Figure.5: Evolution of the resistance of phases versus the soft phase (Co) volume fraction for the system WC-Co in tension

WC-Co in compression

In the compression case of the deformed materials WC-Co, the volume fractions used in training procedure are 43%, 36% and 21% of Co.

The obtained parameters k_α, k_β and n_α, n_β are listed in the table (2).

The comparison between calculated and experimental curves also shows a good agreement between these curves (Figure 6), it also shows that curves corresponding to the volume fractions 40%, 30% and 15% of Co integrate very well in the evolution of the experimental curves.

The variation of the resistances k_α and k_β is illustrated in Figure 7; it can also be accepted that is linear variation in this case.

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Table 2: Parameter values obtained by Fuzzy Logic prediction. WC-Co system in compression

The volume fraction of Co (%)	K_α (MPa)	K_β (Mpa)	n_α	n_β
40	456.0	4350.0	0.8	0.6
30	1090.3	4780.6	0.6	0.7
15	2490.6	5354.2	0.7	0.7

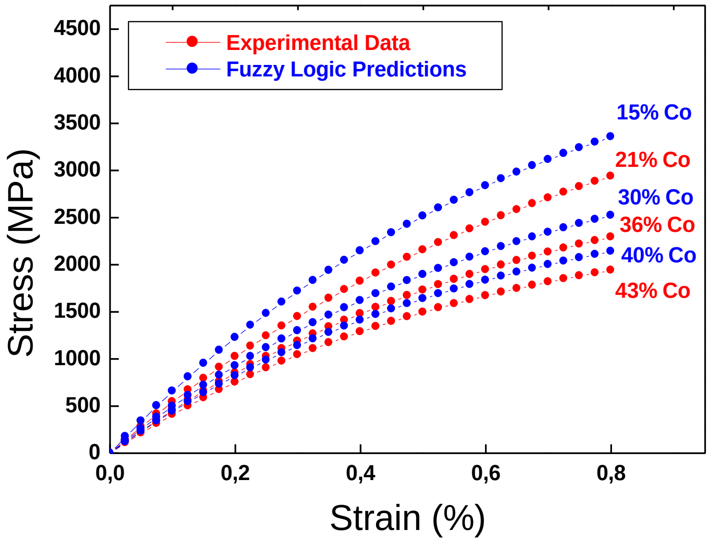

Figure.6: Predicted stress-strain curves. WC-Co system in compression (experimental data (Doi et al., 1969)

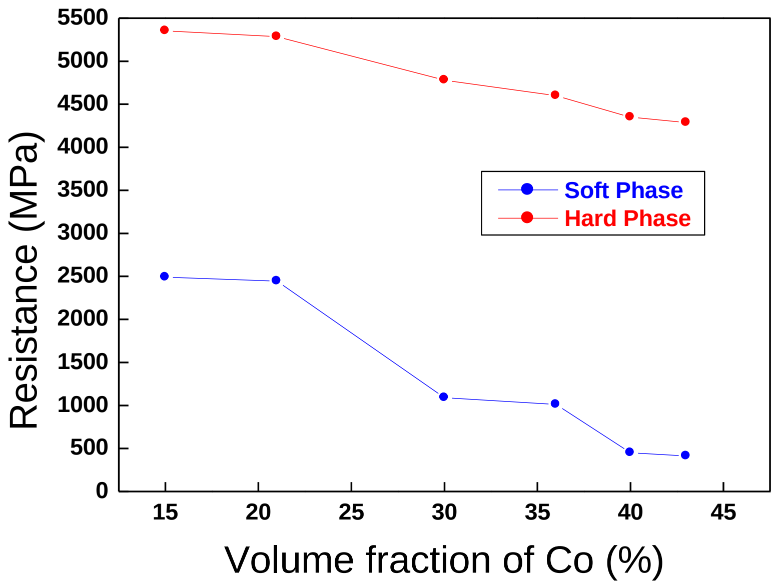

Figure.7: Evolution of the resistance of phases versus the soft phase (Co) volume fraction for the system WC-Co in compression

The phase resistance evolution behaves differently in the tension and compression cases; this difference is due to the difference in the mechanism of deformation of the WC-Co materials in tension and compression tests.

DISCUSSION

The fuzzy logic approach has allowed building theoretical stress-strain curves of WC-Co two-phase materials as a function of Co volume fraction from a few experimental stress-strain curves. This approach can be used to determine the stress-strain curves as a function of Co volume fraction.

The obtained phase resistances increases with the rise of WC hard phase volume fraction; their variation is almost linear, the author proposes a microhardness test to determine experimentally the values of these resistances and compare them with the calculated ones. The increase of phase resistances with the rise of hard phase volume fraction is due to the hardening effect by volume and interface boundaries between the two phases.

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CONCLUSIONS

A fuzzy logic approach was used in this study to predict stress-strain behavior parameters from numerical experimental stress-strain curves. This approach has allowed determining the four mechanical parameters: resistances and adjustment parameters that allow predicting the stress-strain curves of WC-Co two-phase materials deformed in tension and compression as a function of Co volume fraction. The agreement of the evolution of predicted stress-strain curves is very satisfactory with the evolution of experimental curves. The determination of the four mechanical parameters of the exponential form has allowed predicting theoretical stress-strain curves of soft-matrix two-phase materials with no corresponding experimental ones. A comparison of theoretical values of resistances with values of experimental micro hardness in each phase is a feasible future study.

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