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Phase Transformation under the Influence of the Plastic Deformation in Al-22at.% Zn Alloy in the Presence of Cu-additions

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ABSTRACT

The plastic deformation effect on the phase transformation (grain boundary diffusion) for Al-22at.%Zn polycrystals in the presence of copper additions have been investigated in the range of aging temperature 303-513K under the solvus line of the alloy (557K). The copper additions are 1, 1.5 and 2 at.% of the alloy. Also, the degrees of plastic deformation involved by rolling are 5, 10, 15 and 20%, respectively. The occurrence of the discontinuous precipitation reaction has been effective by the degree of plastic deformation and the addition of copper. The phase constituents involve the FCC Al-rich, HCP Zn-rich and $CuZn_4$ phases. The cell growth rate of discontinuous precipitation reaction of Al-Zn-Cu alloy is affected by the copper addition. The growth rates are higher by one order of magnitude than the value at the lowest aging temperature (303K). This is compared to the growth rate at zero plastic deformation. The experimental measurements of nucleation and the growth of the discontinuous precipitation with cold rolling occur. The grain boundary diffusivities determined are in good agreement with the radiotracer measurement data in the Al-Zn systems. While the values of the activation energy, Q_o, of the discontinuous precipitation reactions are -35.94, -39.71 and -45.36KJ/mol. The values of the pre-exponential factors, $(S\delta D_b)_o$, are $2.962*10^{-12}$, $3.21*10^{-12}$ and $6.53*10^{-12}$ m^3/sec with cold rolling of 5,10, 15 and 20 percent, respectively.

Keywords: Plastic deformation, discontinuous precipitation reaction, growth rates, interlamellae spacing, Al-Zn-Cu alloy.

1.INTRODUCTION

Recently, the Al-Zn alloys are being commonly used in aircraft, automobile, and space industries due to their desirable properties like high strength to low density, satisfactory toughness, and stress corrosion cracking resistance. The highly passable precipitation mechanism in Al-Zn-Mg-Cu alloys can be defined by chronological appearance of supersaturated solid solution (SSS) - GP zone - metastable η' - stable η ($MgZn_2$) [1–4]. A binary solid solution α_o may relieve its thermodynamic metastability through a solid-state decomposition process, including nucleation and growth of a precipitate ß-phase providing the solute redistribution is possible under the provided thermodynamic and kinetic conditions. This precipitation reaction happens at a significant modification in the microstructure, composition, and phase stability, and consequently, a noticeable improvement in material characteristics and performance. Fig. 1 shows the classification of the heterogeneous solid-state transformations in particular the moving boundary reactions [5–7].

The discontinuous precipitation reaction (DP) is leading to the isothermal decomposition of α_0 in (α+ß) aggregate involving varied precipitation of ß on the reaction front as shown in Fig. 2. Consequently, DP reaction is a solid-state reaction controlled by boundary diffusion which starts at large-angle-grain boundaries (GBs). During this reaction, an initially homogeneous supersaturated solid solution, α_0, decomposes behind the reaction front (RF) into a two-phase structure, (α+ß). The morphology of the two-phase structure is usually lamellar; however, in some cases it is rod-like. Where ß- phase is the precipitating phase which can be an intermetallic compound or a solid solution of the same or different crystal structure as α_0 and α is the depleted solid solution [1–3,5–8].

Jarzębskaet et al. [7] displayed the effect of plastic deformation and aging time on the mechanical properties as well as microstructure of the alloy AA7050 by age hardening throughout that are formed coherent and semi-coherent particles that lead to higher strength. Major effect on the precipitation processes and enhance the strength have a plastic deformation after solution heat treatment.

Discontinuous precipitation in Al-Zn system is distinguished by different metastable phases formed and is affected by the quench rate, homogenizing temperature, and quantity of impurity. The Al-Zn alloys does not be homogeneous after quenching, due to the fluctuation of αo concentration in the matrix. That are known by the Guinier-Preston- zones or pre-precipitation stage which will be affected the growth of cellular precipitates [2,4].

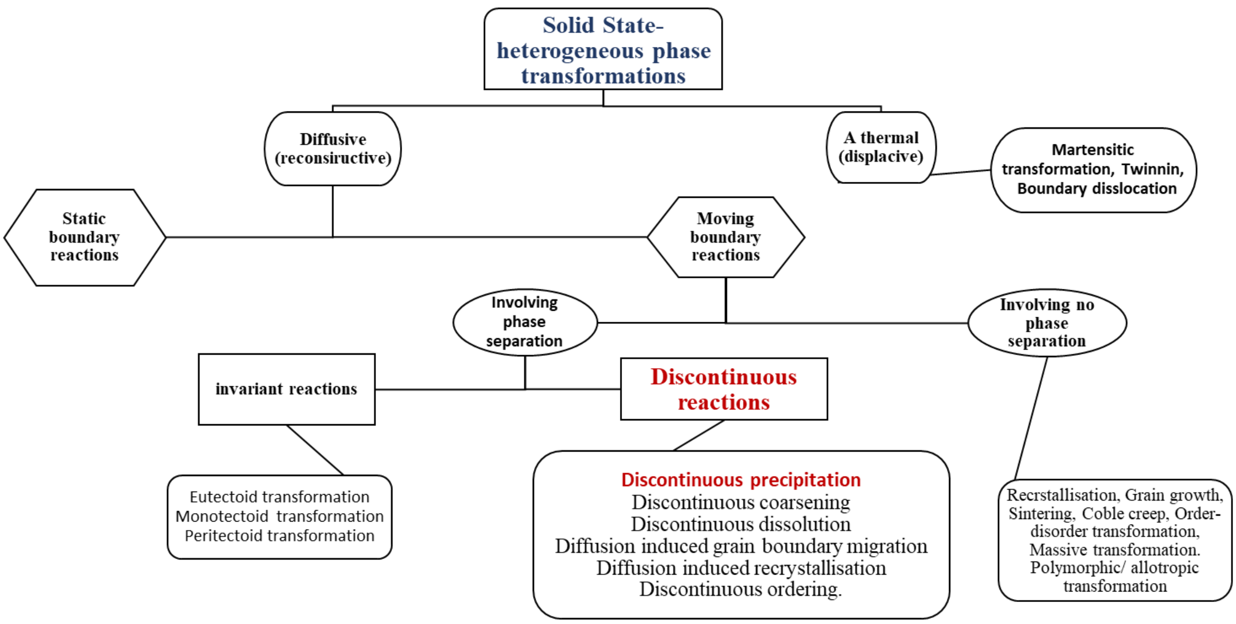


Fig. 1: Flow chart of solid-state diverse phase transitions [2].

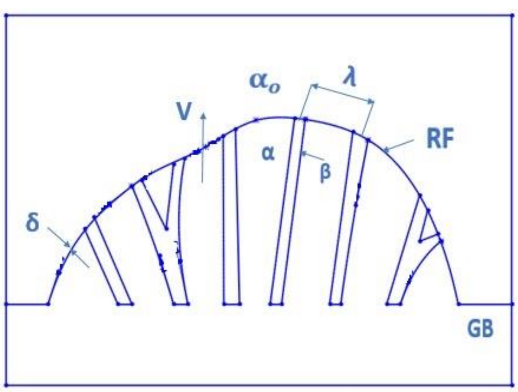


Fig. 2: Illustration of discontinuous precipitation happening at grain boundary (GB) and growing behind a migrating reaction front (RF) progressing into a supersaturated α0 grain [1–7].

The formation of the equilibrium phase ***β***-rich element Zn, appear first with metastable GP-phases form of segregation or clusters that retain the structure of the solid solution $\boldsymbol{\alpha}_0$ and are fully consistent and second phase appears in R. The formation sequence of precipitate in the solid solutions of Al-Zn system as follows [1,2].

Plastic deformation for alloys is very important because it is the main component of numerous of the industrial engineering processes. the plastic deformation effect on the discontinuous precipitation reaction is required to evaluate the influence of the resulting rolling percent and impurities [6,7,9–11].

Plastic deformation has a major impact on the growth rates of the discontinuous precipitation which in turn has a great effect on the mechanical properties behaviour of the aluminum-zinc alloys [1]. There is little information available for the influence of plastic deformation on the behaviour and driving force of the discontinuous precipitation reaction, especially when including impurities [11,12].

The plastic deformation led to defects in the matrix structure such as dislocations, which increase the favorable sites for cellular precipitation reaction. For this the dislocations are aligned to form additional new grain boundaries, led to decomposition for phases. Moreover, in some another alloys, the restrain delays or eliminates the discontinuous precipitation reaction [10].

From the metallurgical view, plastic deformation creates dislocations and therefore strains in the matrix. The prior plastic deformation may either enhance or reduce the discontinuous precipitation (DP) growth kinetics, depending on whether the stored strain energy improves the driving force for DP or promotes continuous precipitation over discontinuous precipitation, respectively [11,13].

Manna et al. [12] studied the precise origin of the alloying additions affected the discontinuous precipitation kinetics with supplements of Sb and Cd to a Pb-9.87 at% Sn alloy. The resistomtric measuring of the precipitation kinetics, by microstructural observations, evidence that the dramatic reduction in the reaction rate is independent on the atomic size or the valence electron difference that caused by the Sb or Cd addition. The ternary elements segregation at the sweeping reaction fronts seems to delay and ultimately terminate the discontinuous precipitation process at the premature stage.

Hao et al. [13] studied the influence of copper additions on discontinuous precipitation of Al-Zn alloy using X-ray diffraction, optical, and scanning electron microscopies. It is discovered that the effect of 2.0% copper on cellular nucleation site is not noticeable, while the of aging temperature effect is evident. The cell growth rate of DP in Al-Zn alloy is surprisingly accelerated with addition of 2.0 at.% copper. Also, the phase constituents contain a phase mixture of the terminal FCC Al-rich phase (α_o), HCP Zn-rich phase (β) and $CuZn_4$ phase in the quenched and aged Al Zn-2.0%Cu alloys [11,13,14].

The driving force of discontinuous precipitation, which is associated with the change of free energy, is affected by the plastic deformation of a quenched solid solution [15].

Aluminum-zinc was selected for the present study due to the discontinuous precipitation reaction is generally took place at low aging temperature and relatively short aging time and in addition it is easy deforming by rolling. An essential condition for each precipitation process has always been the solubility of the second component changed with temperature as concluded by Abdou [6].

The present paper is focused on the effect of plastic deformation on the discontinuous precipitation reaction in Al-22at.%Zn polycrystals in the presence of copper additions as the third element to the alloy.

2.EXPERIMENTAL DETAILS

2.1. Material

The Al-22at.%Zn alloys containing 1, 1.5 and 2 at.% Cu were prepared from 3N Al , 4N5 Zn and 3N4 Cu by melting in an inert atmosphere (argon). The castings were 15mm in diameter and 110 mm length. The ingots were cold rolled to 6 mm thickness and then homogenized at temperature 555k for 21 days and quenched in an ice-salt-methanol mixture (258-263K). The specimens were cut into a size of 5x5x15 mm for the present study. The chemical composition of the specimen alloy is given in Table 1.

2.2. Heat Treatment

The aging of specimens was performed in an oil bath or a salt bath; nitric acid system (KNO_3+ $NaNO_3$) at the temperature range of 323-513K for discontinuous precipitation (DP). Also, treatments were performed in choleric acid system ($BaCl_2$, KCl and NaCl) in the same range of temperature. Aging treatments shorter than 10 hours were carried out in salt bath whereas for the longer aging the quenched specimens were sealed aging in quartz tube under high vacuum and annealed in horizontal furnace. The specimens were wrapped in oxidized aluminum foil to prevent a reaction with the molten salt or the oil. Before aging, the specimens were subjected a final homogenization treatment for 2h at 625K according to the strategic plane. The specimens (5x5x15 mm) were homogenized for 21 days at 625K. Finally, they were quenched in an ice-salt mixture (258K). The heat treatment procedure is schematically displayed in Fig. 3. The plastic deformation by rolling was applied before aging.

Table 1: Chemical composition of the Al-Zn-Cu alloys

Element (at.%)	Zn	Cu	Mg	Si	Fe	Ni	Al
Group I	22	2	2.02	0.08	0.50	0.95	Bal.
Group II	22	1.5	2.05	0.075	0.48	0.95	Bal.
Group III	22	0.5	2.00	0.078	0.48	0.95	Bal.

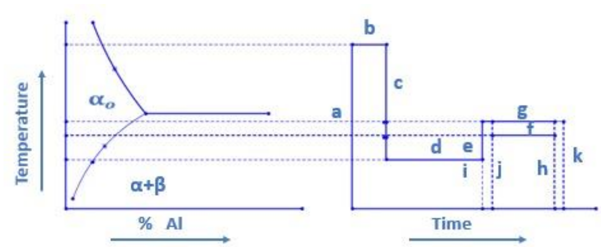


Fig. 3: The heat treatment procedures. (a,c,e,h,I,j,k) Up heating or down quenches;(b) Homogenization anneal;(d) Precipitation anneal and (f, g) Solution anneals above solvus line(at two alternative temperature ranges).

2.3. Metallography

The metallographic specimens were prepared by grinding and polishing through 6 µm down to 1 µm diamond paste. The specimens were heated before etching in hot or boiling water to enhance the etching effect, then etched using an etching reagent (32.5% HNO_3 in distilled water) for 30-90 sec.

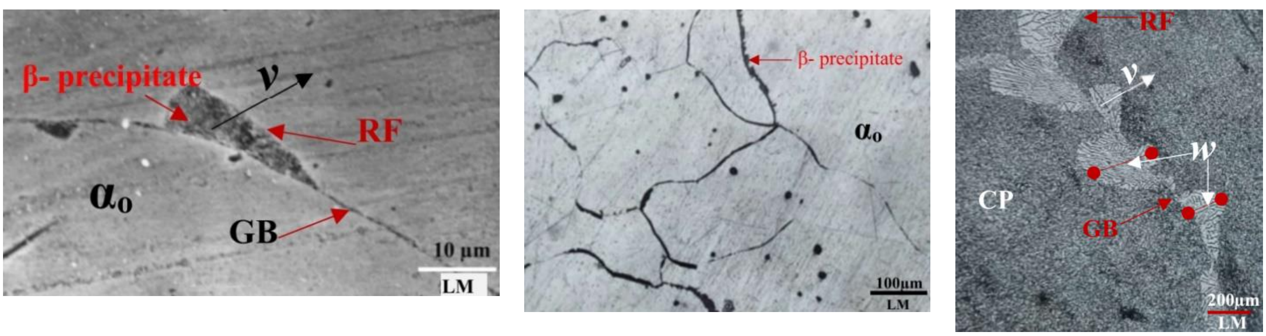
3.RESULTS AND DISCUSSIONS

3.1. Metallography

The discontinuous precipitation reaction in these quenched and aged Al- Zn-Cu alloys is a phase mixture (α_o), HCP Zn-rich phase (β) and $CuZn_4$ phase. The nucleate of precipitation start at the grain boundary interfaces and then grow at the expense of the single phase α_o-matrix, Fig. 2. Fig. **4** (a,b) are light micrographs showing the discontinuous precipitation reaction in an ice-salt quenched and aged specimen which was in the process of growing into the untransformed matrix at 303K for 300 sec and 423K for 600 sec, respectively for undeformed Al-Zn-1.5Cu alloy. While Fig. 4-c shows the initiation of S-Mechanisms for the discontinuous precipitation reaction (DPR) which grow into the continuous precipitation reaction (CPR) for undeformed alloy. Fig.5 shows light and SEM micrographs of the discontinuous precipitation in deformed Al-Zn-Cu alloy with addition of 2.0 at.% copper. The nucleation begins at grain boundaries, sub-grain boundaries, and at isolated points within the grains proper, which are free of such interfacial structural lattice defect. Three modes of the precipitation process in aluminum alloy containing 22at.% Zn and different addition of copper are observed: precipitation on dislocations; precipitation on grain boundaries; and discontinuous precipitation reaction at grain boundaries as shown in Fig.5 and Fig. **6**. The discontinuous coarsening reaction (DC) also occurs with increasing the aging time as shown in Fig. 6 (a, b).

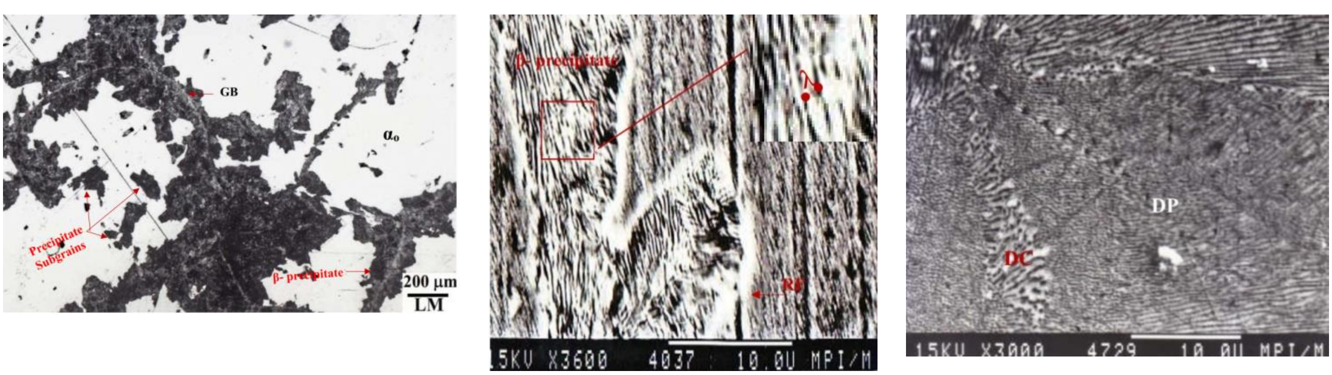
3.2. Growth Rate

The arithmetic mean of the discontinuous precipitation (DP) seam width (w`) has been determined from 15-25 measurement readings [2–4]. The width of the discontinuous precipitation seam versus the aging time for undeformed Al-Zn-Cu alloys is plotted in Fig. 7.



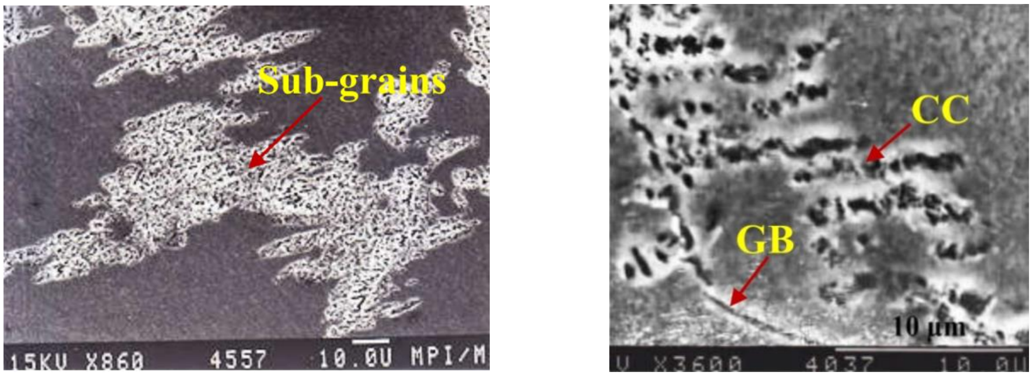
a) aged at 303K for 300 sec b) aged at 403K for 20 min, c) aged at 543K for 56 s (S-mechanism)

Fig. 4: Light micrographs (LM) showing the occurrence the discontinuous precipitation in undeformed Al-22Zn-1.5Cu alloy.



a) aged at 303K for 10 min, 10 % deformed b) aged at 393K for 120min, 15% deformed c) aged at 423K for 7.5min, 5% deformed

Fig.5: Light (LM) and SEM micrographs showing the occurrence of the discontinuous precipitation reaction in deformed Al-22Zn-2Cu alloy.



a) aged at 363K for 12h, 15% deformed b) aged at 333K for 12h, 20% deformed

Fig. 6: SEM micrographs showing the nucleation of discontinuous precipitation at grain boundaries and subgrain boundaries for Al-Zn-1.5Cu alloy.

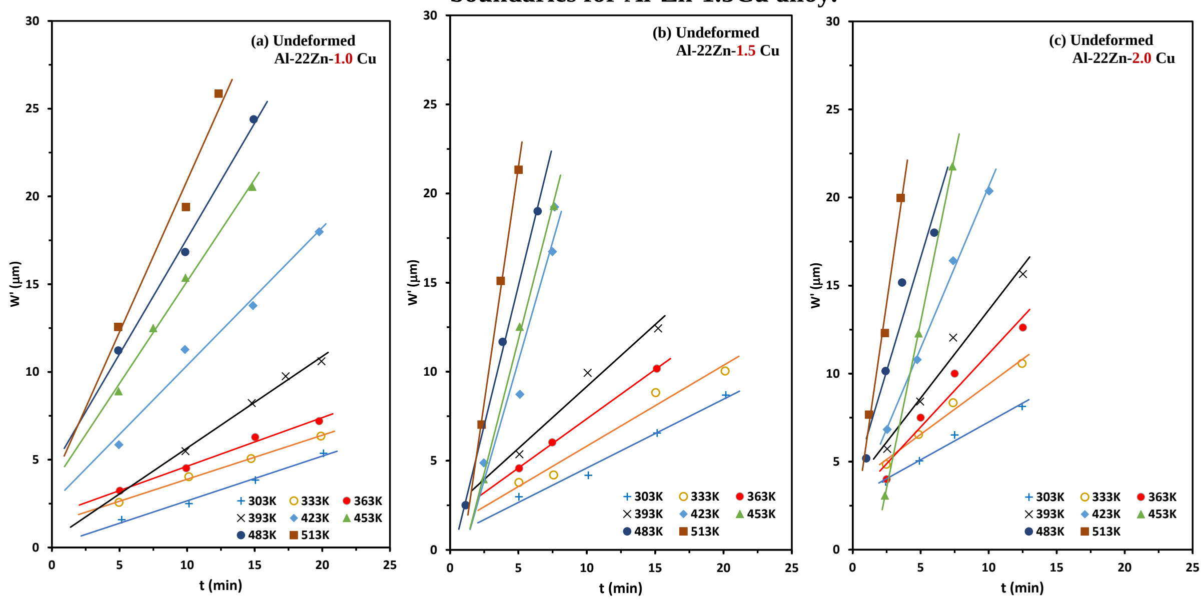


Fig. 7: The width of the discontinuous precipitation seam against the aging time for undeformed Al-22Zn-xCu alloys at different aging temperatures (K).

Moreover, for example, Fig. 8 presents the effect of the aging time on the width of the discontinuous precipitation for rolled deformed Al-Zn-1.0Cu alloys. The first two cases are normal for a nucleation and growth process. The “negative” incubation time is only apparent. A similar behaviour occurs in Ni-In alloys during the discontinuous precipitation reaction due to the branching and distribution of the interfacial driving force [2]. This is due to the new deforming driving force for the reaction. These values are obtained using micrographs in different places around grain boundaries only, not on subgrain. The incubation period for the discontinuous precipitation reaction decreases at higher aging temperature or at rising degree of supersaturation. It will be shown that the growth rate is determined via the slope of the seam width against the aging time [4].

The growth rate for discontinuous precipitation reaction (**v**) obtained from the slope of the distance-time graphs is represented in Fig. 9 as a function of the reciprocal absolute aging temperature (T). Fig. 9(a-c) shows the relationship between the growth rate, **v**, of discontinuous precipitation reaction and the degree of deformation versus the reciprocal absolute aging temperatures (T) in Al-Zn-xCu investigated alloys.

The results show that the growth precipitate rate increases with the increase of the rolling percentage. This is due to the resulting driving force ΔG_1 which occurs due to deformation which is agreed with the previous works [5,6]. The growth behaviour for the Al-22at.%Zn with addition copper has an approximately “C-Curve “behaviour. These curves agree, approximately, with the conclusions of other investigators [15–17]. The relationship between the growth rate of discontinuous precipitation reaction and the degree of deformation in the presence of copper additions versus the reciprocal absolute or with aging temperature in Al-Zn-Cu alloys shown in Fig. 9. Moreover, another form of the relationship between discontinuous precipitation reaction of the growth rate (***v***) and the copper additions at various degree of deformation is presented in Fig. 10. Whereas the symbols present the measured values, the lines present the predicted values by Eq. (2) provided from a regression model.

3.2.1. Regression Model

A regression model is performed for the growth rate for discontinuous precipitation reaction in the presences of cupper addition and deformation.

The experiments were carried out on Al-22at.% Zn alloy with different levels of three parameters: aging temperature, degree of plastic deformation by rolling (d), and copper additions (Cu). The effect of these parameters on the growth rate (v) was studied.

Statistical regression using a quadratic expression, Eq. (1), was used to define the relationship between experimentally measured precipitation velocity (v) and the studied parameters.

$$ln(v) = a_o + a_i x_i + a_{ij} x_i x_j + a_{ii} x_{ii}^2 \qquad (1)$$

where: ‘a_0’, ’a_i’, ‘a_{ii}’ and ‘a_{ij}’ are the regression coefficients, and ‘x_i’ and ‘x_j’ are the i^{th} and j the values of the input parameter, respectively.

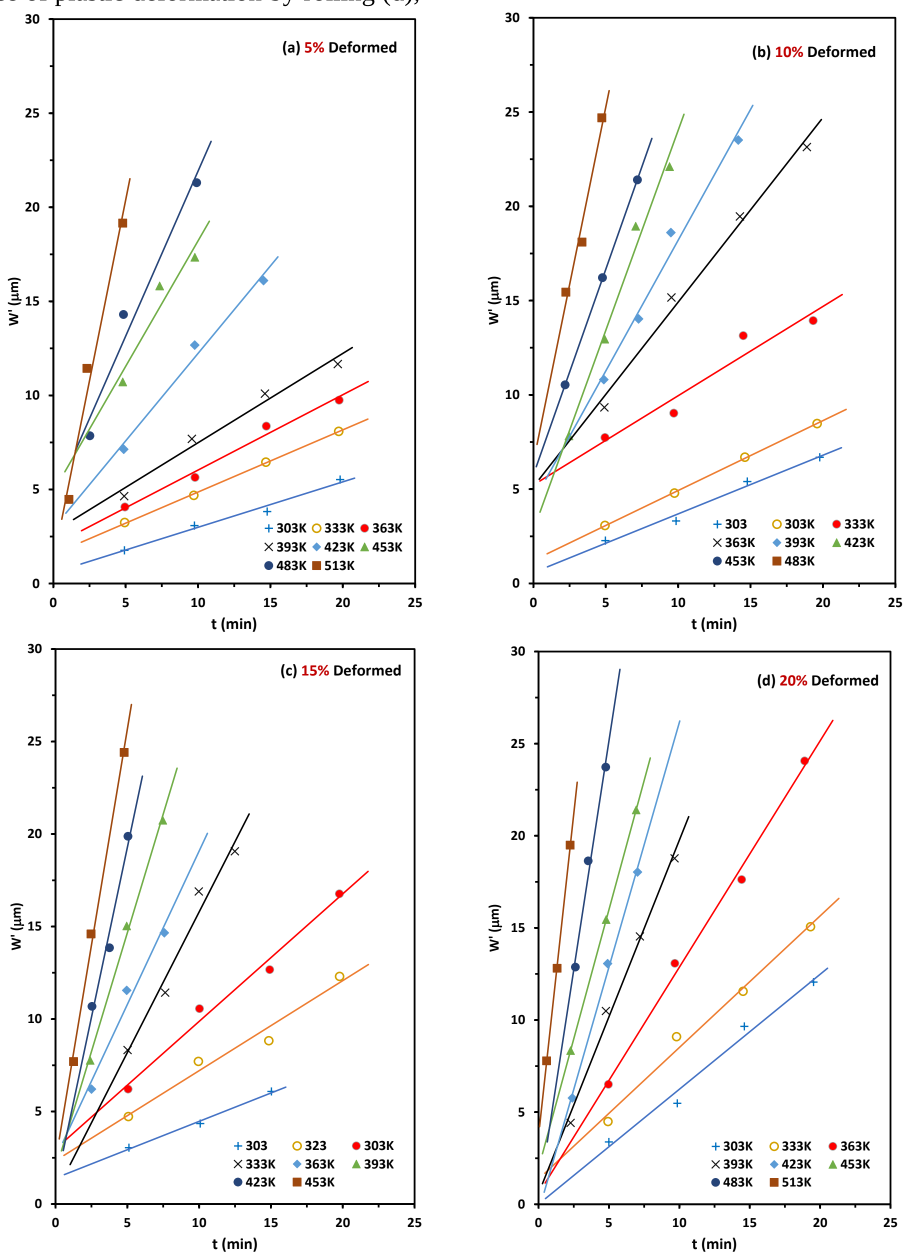


Fig. 8: The width of the discontinuous precipitation seam against the aging time for Al-22Zn-1.0 Cu alloy, deformed at various cold rolling percentages and different aging temperatures (K).

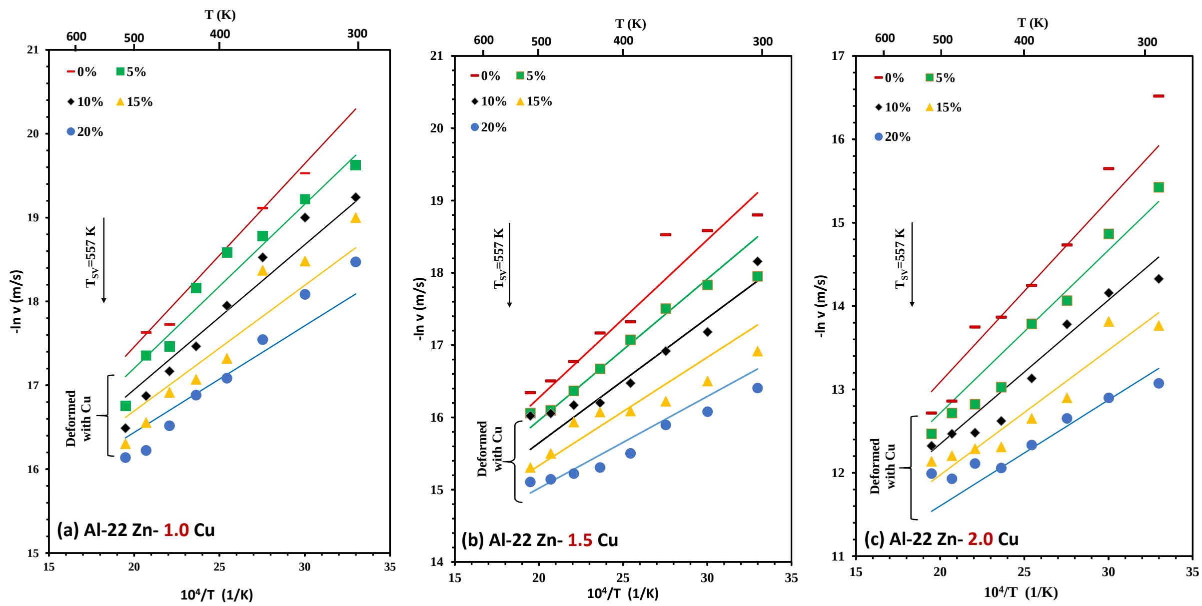
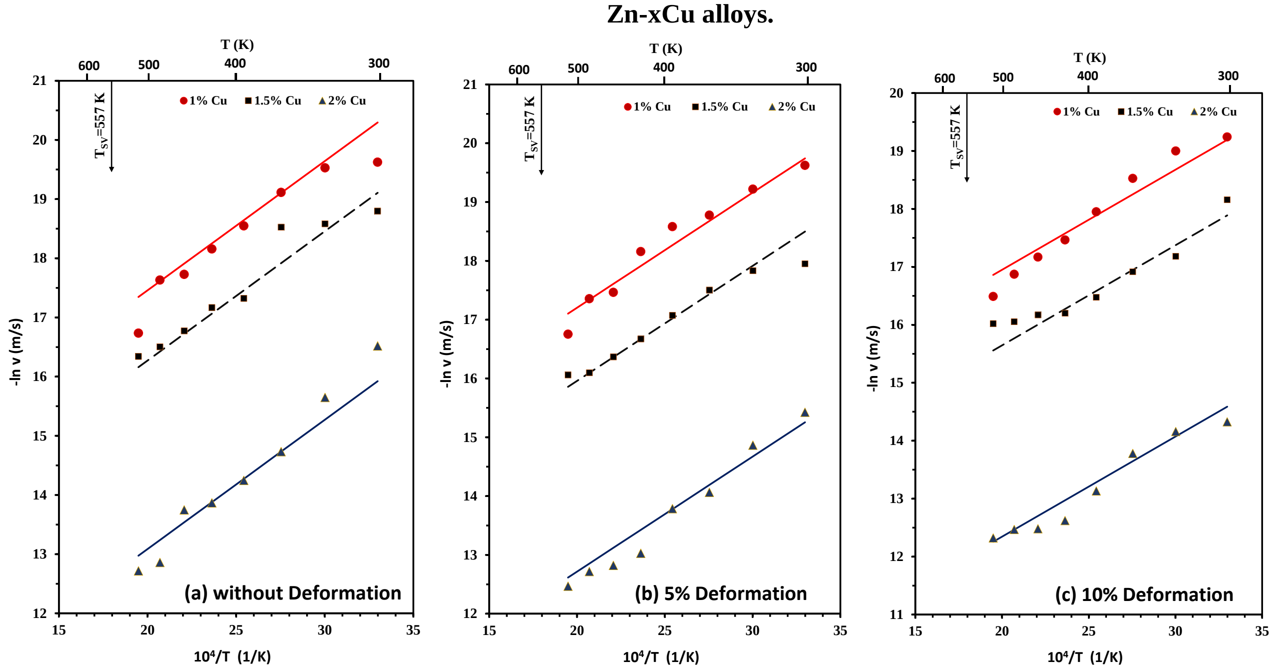


Fig. 9: The relationship between the growth rate of discontinuous precipitation reaction at various degree of deformation in the presence of copper additions versus the reciprocal absolute aging temperature in Al-Zn-xCu alloys.



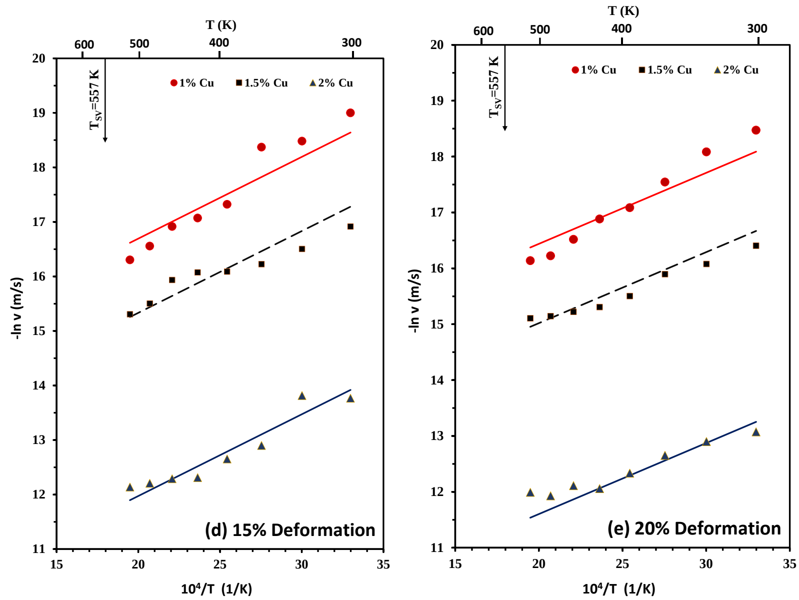


Fig. 10: Effect of the copper additions on growth rate of discontinuous precipitation reaction and various degree of deformation at the reciprocal absolute aging temperature in Al-Zn-xCu alloys.

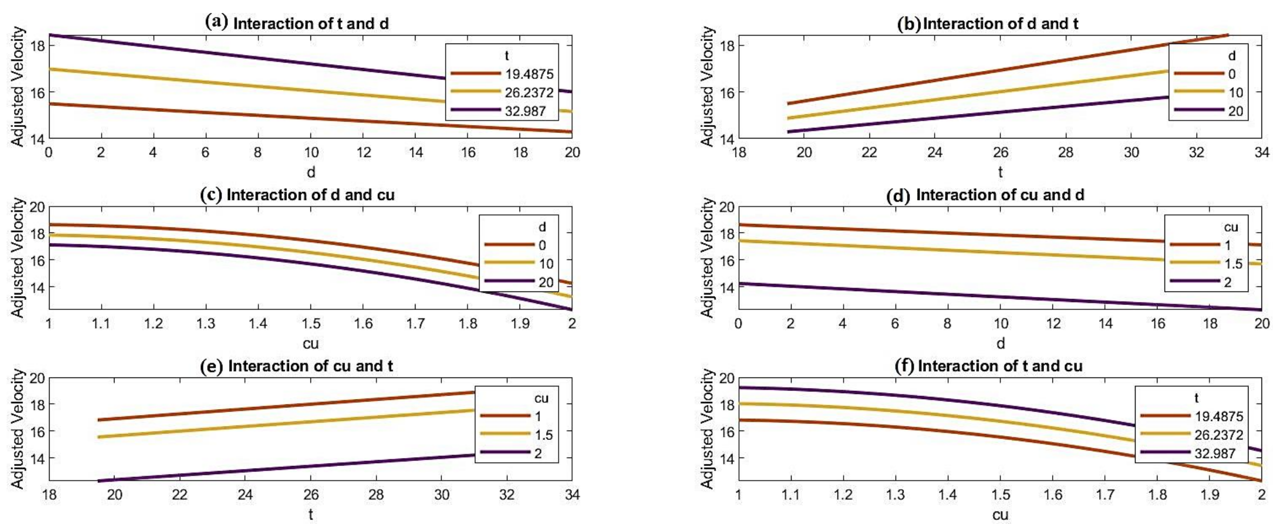


Fig. 11: Plots depicting the interactive effects of temperature (t= 104/T),deformation percent (d) and copper atomic percent (cu) on velocity (lnv);(a) the effect of temperature at different levels of Cu, (b) the effect of Cu under different levels of temperature, (c) the effect of deformation at different levels of temperature, (d) the effect of temperature under different levels of deformation, (e) the effect of Cu at different levels of deformation and (f) the effect of deformation under different Cu.

To develop a robust quadratic regression model for three process parameter inputs (aging temperature (10^4/T), deformation percent (d), and copper atomic percent (Cu) requires 10 terms at least. Equation (2) shows the predicted values of velocity(m/s) at all the three variables.

The regression model Eq. (2) was then used to analyse the effects of the different input conditions, singly and in combination, on the measured velocity.

$$ln\ v = 3.996\ Cu^2 - 0.2184\ t - 0.06362\ \mathrm{d} - 7.6161\ Cu + 0.0045687\ t\ d + 0.023212\ d\ Cu - 9.4701 \qquad \textbf{(2)}$$

Where '***v***' is the predicted growth rate for discontinuous reaction considering the degree of deformation (*d*), copper additions (*Cu*) and temperature (10^4/T*)*; R-squared was 0.989, and adjusted R-squared was 0.988. Fig. 11 (a-f) illustrates the effect of process parameters and their interactions on measured velocity (*ln v*).

From Fig. 11 (a, b), it is noticed that the temperature is an effective variable where the velocity decreased and with increasing the temperature (T), whereas the increase of the deformation percent lead to decreased of the precipitation velocity at various aging temperatures.
The effect of copper percent above 1.5% for various aging temperature is shown in Fig. 11(c, d). The interactive between Cu and deformation percentages were shown in Fig. 11 (e, f). the deformation (d) showed insignificant effect with the copper additions whereas the copper additions play an important role at 2.0%.
The measured and regression model, Eq. (3), established for predicting precipitation growth rate (*v*) were plotted in Fig. 9 and Fig. 10.
The arithmetic means for the interlamellae spacing (ƛ), of the discontinuous precipitation (DP) have been determined from 10-15 measurement readings [1–3,8] as shown in Fig. 12. The error bar presented the deviation between undeformed samples and that subjected to various deformed percentages which it is in ±5%. Therefore, it can be noticed that the rolling percentages have no effect on the interlamellae spacing. This led to that the effect of the plastic deformation only on the reaction after aging.

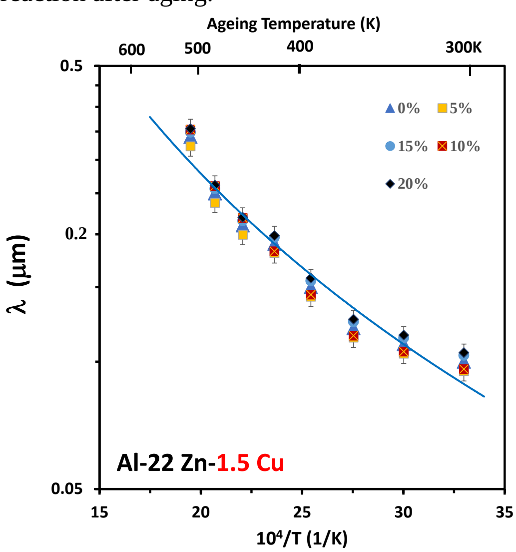


Fig. 12 Effect of aging temperature on interlamellae spacing, for deformed and undeformed Al-22Zn-1.5cu alloys.

3.3. Driving Force and Grain Boundary Diffusion

Grain boundary segregation effects for ternary additions on discontinuous precipitation reaction have been studied [18–21]. Such effects are manifested in the following facts: Decreasing the grain boundary energy, Decreasing the grain boundary mobility, Raising the recrystallization temperature; and, in turn, the activation energy for boundary migration, Increasing the activation energy for the binary solute atom boundary diffusion leading to slowing diffusion, arresting nucleation reactions sites in forms of steps or ledges onto grain boundaries.
All these facts will be results, separately or combined, in interference with the discontinuous reaction. However, there is no immediate explanation for ternary additions which decrease or increase the rate of boundary migration which not documented in several systems [9,22–24].

Hornbogen [23] may be the first researcher to consider the boundary structure affects the ternary element segregation. Also, it is observed that different cells grow at various rates on different boundaries [23]. Kunze et al. [25] proposed that the presence of ternary elements affects the discontinuous reaction by the activation energy for boundary migration. Elements differing slightly in atomic radius were discovered to speeds up the discontinuous reaction in Ag-Cu, lowering the activation energy. On the other hand, elements differing significantly in atomic radius increase the activation energy and thus reduce the precipitation rate. Predel et al. [24] found that in many interface-controlled systems the difference in free energy changes is given by the following relation.

$$\Delta G_1 = \Delta G_{tenary} - \Delta G_\sigma \qquad (3)$$

Chigasaki et al. [26] have argued that ternary elements which elevate the recrystallization temperature, T_R, will quell the discontinuous precipitation reaction. This is obviously associated with the effect of the grain boundary, instead of the precipitate, on the discontinuous reaction. Then, elements that strongly segregate usually raise the recrystallization temperature, T_R, through a solute drag effect [19].
Hultgren [17] concluded that the kinetics reaction during ternary transformation of austenite was due to the behaviour of the alloying elements for transformation. At high temperatures, it is natural to expect that exists once of complete chemical equilibrium at the phase interfaces and a partitioning of the alloying elements between the matrix and the growing phases could be expected. While at low temperatures, the sluggish alloying element may not have sufficient time for diffusion since the growth rate depends on the ternary diffusion. The effect of a given alloy addition on the phase transformation should be expected to decrease considerably when this situation is established at low ageing temperature.
The chemical free energy ΔG_1^c for the discontinuous precipitation reaction is given in the following equations.

$$\Delta G_1^c = \Delta G_e^c \left(1 - \left(\frac{\{x_1 - x_e\}}{\{x_o - x_e\}}\right)^2 \right. \qquad (4)$$

$$\Delta G_1^c = -RT \left[x_o \ln\frac{x_o}{x_e} + (1 - x_o) \ln\frac{1 - x_o}{1 - x_e} \right] \left[1 - \left(\frac{x_1 - x_e}{x_o - x_e}\right)^2 \right]$$
(5)

Where *R* is the gas constant, *T* is the absolute aging temperature, x_o is the original concentration, x_1 is the concentration of depleted and x_e is the equilibrium concentration.
Then, for the discontinuous precipitation reaction the total change in the Gibbs free energy, ΔG_1 , is equivalent to the

decrease in the chemical free energy, ΔG_1^c plus the surface free energy increase, σ, associated with interlamellar boundaries introduced by the relation due to the copper addition is given by the following relation.

$$\Delta G_1 = \Delta G_1^c + \frac{2\sigma V_m}{\lambda} \qquad (6)$$

Where, V_m is the molar volume and σ is the free energy per unite area of the α/ß interface. The surface free energy of the surface between the α and β phase in discontinuous precipitation due to the copper addition may be calculated employing equation.

$$\sigma = H_\sigma + TS_\sigma \qquad (7)$$

Where H_s and S_s are the enthalpy and entropy values determined by Cheetham and Ridley [27] for the surface between αand β-phases in the lamella precipitate eutectoid. These values are 0.72 J/m and 0.66 mJ/m, respectively.

The chemical free energy change, ΔG_e^c, for the precipitation reaction, decreases (increases in magnitude) rapidly with under cooling below the solvus temperature to a value on the order of 1000, 850 and 700 J/mol for the lowest aging temperature for copper addition 1, 1.5, and 2at.%, respectively. The positive surface energy term ΔG_1^σ, on the other hand, is very small and increases to a value on the order of 50 J/mol.

It is noticed that most of the total available free energy (ΔG_1), Fig. 13, is used in the discontinuous precipitation reaction.

Petermann and Hornbogen [28] theory gives the growth of cells of discontinuous precipitation reaction given by;

$$v = \frac{-8\Delta G_1}{RT} \cdot \frac{S\delta D_b}{\lambda^2} \qquad (8)$$

Where, v is the velocity of the reaction front, D_b is the boundary chemical diffusivity in the reaction front, δ is the thickness of grain boundary, S is the segregation factor [23], ΔG_1 is the driving force for the reaction, λ is the interlamellar spacing of the product, R is the gas constant and T is the absolute aging temperature.

The determined values are plotted in Fig.14. The Arrhenius parameters determined for the discontinuous precipitation reaction are as follows: the pre-exponential factor, $(S\delta D_b)_o$, and the activation energy can by calculated from Fig. 14.

The formal energy of activation, Q, can be calculated as:

$$v = v_o e^{-Q/RT} \qquad (9)$$

Where R is the universal gas constant and T is the absolute aging temperature (K).

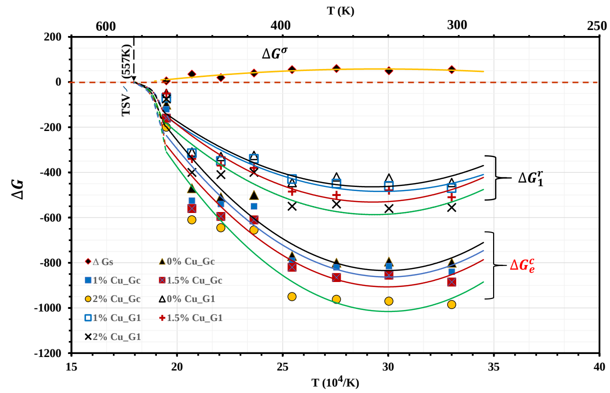


Fig. 13: Gibbs free energy of migrating grain boundaries for discontinuous precipitation reaction and the degree of deformation on the presences of copper addition versus the aging temperature in investigated alloys.

3.3.1. A Regression Model

A Statistical regression using a quadratic expression, Eq. (1), was used to define the relationship between experimentally measured exponential factor (SdD_b) and the studied parameters where a regression model is performed in equation (10).

Ln (SdD_b)=0.023948 T+0.16697 d+4.5364 Cu-0.00032467 Td-0.0013571 T Cu+0.034 d Cu-35.848 (10)

Fig. 15 (a-f) illustrates the effect of process parameters and their interactions on exponential factor (SdD_b).

From Fig. 15 (a, b), it is noticed that the temperature is an effective variable where the exponential factor increased with increasing the temperature whereas variation of the deformation percent has insignificant effect the exponential factor is decreased at various temperatures.

The interactive between Cu and deformation percentages were shown in Fig. 15(c, d). The deformation (d) showed insignificant effect with the copper additions whereas the copper additions play an important role at 2.0%. The effect of copper percent is noticed above 1.5% for various temperature as shown in Fig. 15 (e, f).

The measured and regression model data, Eq. (10), established for predicting factor **(SdD_b)** were plotted in Fig.14.

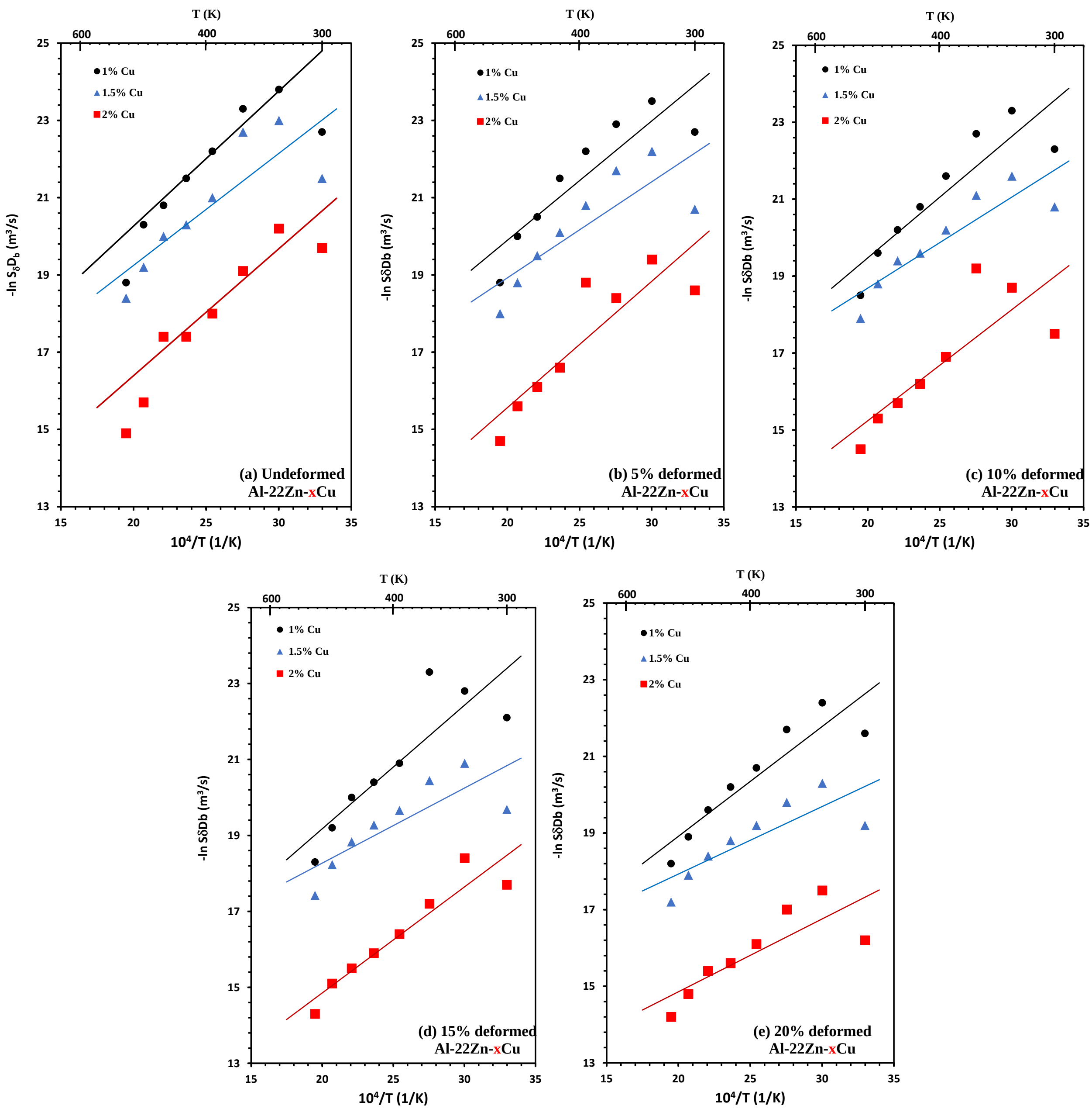


Fig.14: Grain boundary diffusion $(S\delta D_b)o$ and $(S\delta D_b)$ migrating grain boundaries for discontinuous precipitation reaction and the degree of deformation in the presences of copper addition versus the reciprocal absolute aging temperature in investigated alloys, according Petemann and Hornbogen models.

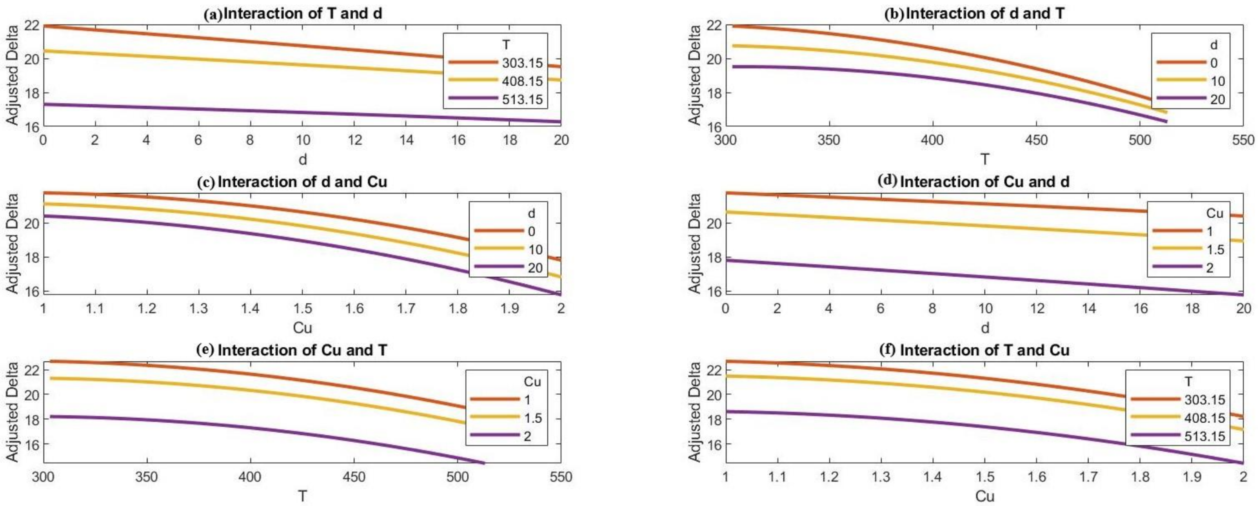


Fig. 15: Plots depicting the interactive effects of temperature T (K),deformation percent (d) and copper percent (cu) on exponential factor(SdD_b).(a) the effect of temperature at different levels of deformation, (b) the effect of deformation under different levels of temperature, (c) the effect of Cu at different levels of deformation, (d) the effect of deformation under different levels of Cu, (e) the effect of Cu at different levels of temperature and (f) the effect of temperature under different levels of Cu.

4. CONCLUSION

Through this work, several concluding remarks and results can be summarized as:

1- Supersaturated solid solution of Al-22 at.%Zn with addition copper alloy in the presence of plastic deformation is decomposed completely by discontinuous precipitation reaction into a lamellar mixture of depleted FCC Al-rich (α_0), HCP Zn-rich (β), and $CuZn_4$ phases during aging at temperatures ranging from 303 to 557K.
2- The nucleation time of the discontinuous precipitation reaction decreases by increasing of the plastic deformation.
3- The contribution of plastic deformation and ageing temperature in the acceleration of the precipitation reaction is clearly, due to the highly strain rates.
4- The growth rate of discontinuous precipitation depends greatly on the degree of deformation, which dependency of identical for each of the aging temperature below the solvus line and the percentage of copper.
5- The growth reaction of discontinuous precipitation reaction has been affected by the plastic deformation and copper additions.
6- The growth rate of the discontinuous precipitation in the existence of plastic deformation usually not follows a “C-Curve” behavior according to the copper addition.
7- The interlamellae spacing have no effect for addition of cupper and plastic deformation
8- Analysis of the growth kinetics, using Petermann and Hornbogen, provides similar results that suggests the reaction is governed by grain boundary diffusion theories at the reaction front.
9- For the deformed alloy, the driving force of discontinuous transformation is increased continuously due to plastic deformation and copper additions.

Credit Authorship Contribution Statement:

Author1: Formal analysis Methodology, Investigation, Writing-Original Draft.

Author2: Methodology, Writing-Review, Software and Editing.

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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