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# Effect of thermomechanical working on the strengthening of some austenitic steel grades

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ABSTRACT

This work studied the effects of degrees of warm-split rolling at different temperatures on the strengths of three different grades of austenitic steels (chrome–manganese, chrome–manganese with Ni and Mo additions, chrome–nickel with Mn and Mo additions). The results were compared with cold-rolling effects on the steel grades. The tensile, hardness and impact strengths of the rolled products were obtained. The results showed that thermomechanical working remarkably influenced the properties of the alloys. The trend in property change was dictated by both the degree and temperature of deformation. It was concluded that warm deformation at 350 °C and degree of deformation between 20% and 30% enhanced the plasticity values (toughness and ductility) of the alloys.





## 1. Introduction

In recent times, and as a result of increasing developments in chemical, oil and gas, heavy machine building industries, and in particular reactors for thermonuclear synthesis, there has been a tremendous increase in demand for a number of non-magnetic, stable austenitic steels, which are also considered perspective materials for the inner walls of the reactors, by virtue of their capability to withstand heavy loads at very high temperatures [1].

Austenitic stainless steels are Fe–C alloys with 16–20% chromium and 8–30% nickel contents, and the structure is usually obtained by direct solidification to austenite ($\gamma$-Fe) or through solid state transformation to delta ($\delta$) ferrite. The direct solidification type is a single phase ($\gamma$ phase), while the solid state transformation type is two phase structure ($\gamma$ and $\delta$ phases).

Austenitic structure or matrix with high delta ferrite phase is magnetic austenitic steel, while the single phase structure is non-magnetic, stable austenitic [2]. Non magnetic, stable austenitic steel types show a number of striking features which make them very suitable as constructional materials for installations operating at relatively high temperatures. These features include; high stability of properties and preservation of austenitic structure under long time thermal exposure, absence of contaminants in the nickel-ion plasma during atomization, relatively low tendency towards formation of vacancy looping and swellings, in comparison with Cr–Ni steels [3]. While little or sometimes no problems are experienced in the application of austenitic steels as constructional materials, operating at moderate temperatures, a number of difficulties accompanied their exploitation at very high temperatures, especially when they are utilized in thermonuclear installations [4]. Undesirable features such as radiation swellings, voids, vacancy looping and solid solution impurities are discovered in austenitic steel parts of thermonuclear installations. These features tend to reduce the high temperature strength of the alloys [5].

In order to check these undesirable features and thus improve the high temperature performance of the alloy in its working environments, a number of methods of preliminary treatment of the alloys prior to application have been suggested [6–18]. These are:

1. The mechanism of arrest of point defects by the introduction of coherent interface that will intensify recombination of vacancies and interstitial atoms by increasing the nickel content of the austenitic steel to 35–60%.
2. Phase-cold work hardening of the austenitic steel prior to any form of utilization. It was soon discovered that consequent upon such treatment the austenitic structure is filled with a large number of twinnings which constitute barriers for dislocations along which the interstitial atoms move. Thus a large number of vacancy loopings are formed around the twinnings causing a lowering of resistance of the alloy to radiation swelling.
3. Cold plastic deformation prior to exposure of the material [8,9]. This was observed, because decreased radiation swelling, and lower the number and size of the pores. The basic factors that counted towards the elevation of the resistance of austenitic steels to radiation swelling, as remarked by them, were the absence of twinning and vacancy looping, increased dislocation

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density, recombination of vacancies and interstitial atoms generated in the alloy as a result of radiation bombardment which eventually created optimal dislocation structure.

4. Holding or blocking the point defects in the material with other atoms whose radii differ appreciably from that of the atoms of the austenitic steel [10,15]. This was observed to minimize radiation swelling and other flaws in austenitic steels. Furthermore, they ascertained that same irregularities may be eliminated by the intensification of the recombination of point defects in elastodistorted regions, and creation of ultrafine grains both achievable by controlled plastic deformation.

Controlled plastic deformation of alloys is seen as the most viable method of grain refinement and elimination of flaws in structural metallic alloys [16], and in the case of austenitic steel, strengthening achieved arises from austenite grain refinement. Optimum properties in austenitic steels are often obtained, if austenite is prevented from recrystallization. In recent times, it has become fashionable to influence and change the mechanical properties of materials by systematic control of the grain structure and size [17].

The effect of the degree of plastic deformation on the mechanical properties of high temperature thermomechanically treated low carbon steel showed that for higher quality of the wrought alloy a large degree of deformation should be employed [18].

The present study examined the response of austenitic steels to warm split plastic deformation.

## 2. Materials and methods

Starting materials were three types of austenitic steels; Cr–Mn, Cr–Mn with Ni and Mo additions (Cr–Mn$^{+}$) and Cr–Ni with Mn and Mo additions (Cr–Ni) all obtained from Universal Steels Company, Ltd., in Lagos-Nigeria. The compositions are presented in Table 1.

The samples were heated to 1100 °C and held for 1 h. at this temperature and thereafter quenched in water. They were then rolled to different deformation degrees of 10%, 20%, 30% and 40% at temperatures of 28, 350 and 650 °C for each degree of deformation.

### 2.1. Mechanical tests

The samples were machined to A 296 ASTM standards for tensile and Izod impact tests. Tests were carried out on the universal tester and Izod impact tester, respectively. Brinnel hardness values for the samples were determined as well.

## 3. Results and discussion

The results obtained in this study are presented in Figs. 1–5. Figs. 1a–c and 2a–c show the effect of the degree of deformation at different temperatures on the offset yield strength, and percentage elongation of the austenitic steel types, respectively. Fig. 3a–c present the variation of impact strength of the materials with the degree of deformation at different temperatures.

Figs. 4a–c and 5a–c represent the effects of the degree of deformation at various temperatures on the ultimate tensile strength and hardness.

### 3.1. Cold deformation of the alloys at 28 °C

At 28 °C and degree of deformation less than or equal 10%, all the steel grades showed improved tensile strength and hardness

**Table 1**
Percentage chemical composition of austenitic steel types

| Steel grade | Chemical composition (wt%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | P | S | Si | Cr | Ni | Mo | Al | Fe |
| Cr–Mn$^{+}$ | 0.12 | 14 | 0.04 | 0.03 | 0.8 | 12.0 | 4.0 | 1.0 | 0.6 | Balance |
| Cr–Mn | 0.04 | 19.0 | 0.04 | 0.03 | 1.0 | 12.0 | – | – | – | Balance |
| Cr–Ni | 0.03 | 2.0 | 0.04 | 0.03 | 1.0 | 16.0 | 9.0 | 2.0 | – | Balance |

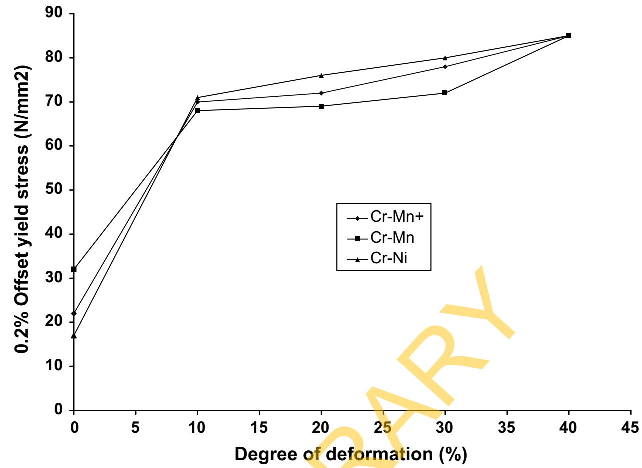


**Fig. 1a.** Variation of 0.2% offset yield stress with percentage deformation at 28 °C.

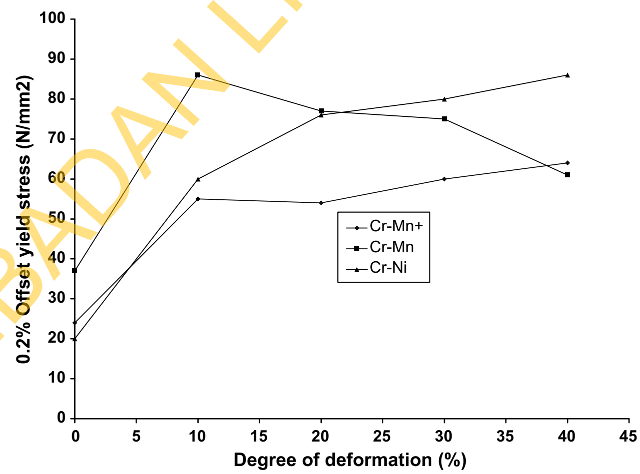


**Fig. 1b.** Variation of 0.2% offset yield strength with percent deformation at 350 °C.

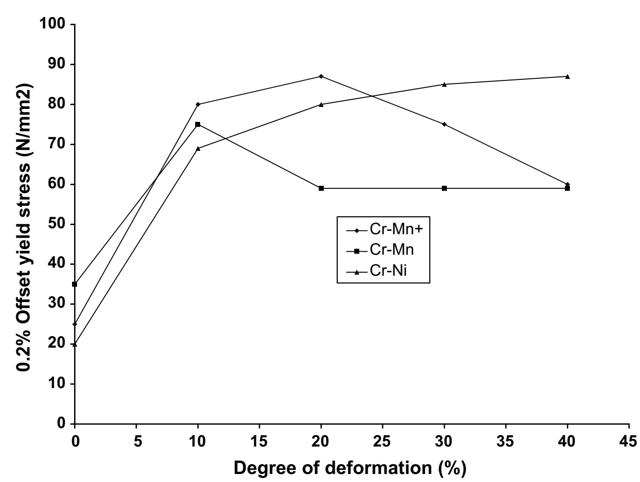


**Fig. 1c.** Variation of 0.2% offset yield strength with percent deformation at 650 °C.

(Figs. 1a, 4a and 5a). The observed trend in the change in strength of the steels is attributable to strain hardening [19]. Strain hardening is due to dislocation movement impeded by various obstacles such as interstitial atoms, precipitated secondary phase, grain boundaries, and other dislocations. The stress field around a dislo-

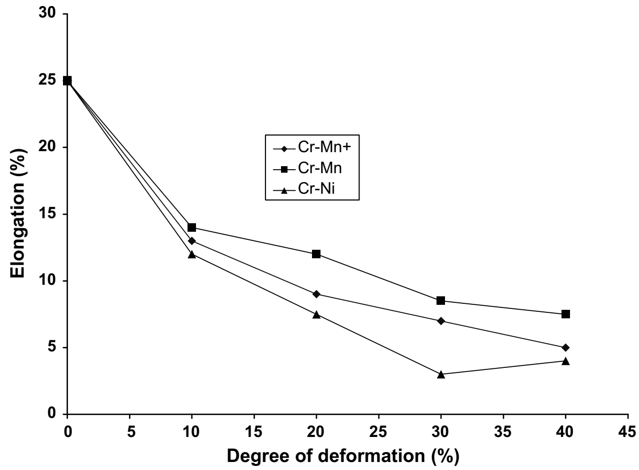


**Fig. 2a.** Variation of elongation with degree of deformation at 28 °C.

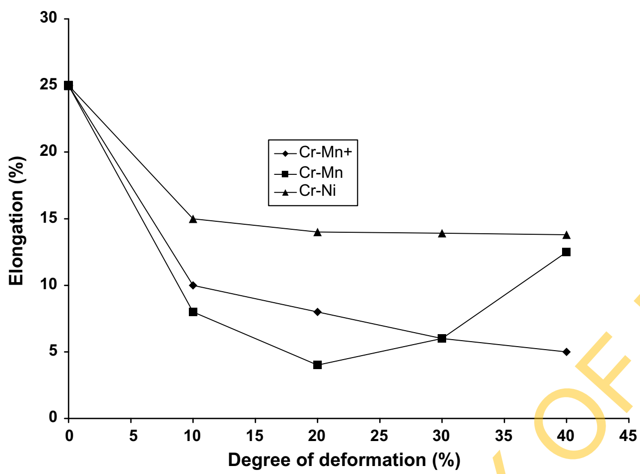


**Fig. 2b.** Variation of elongation with degree of deformation at 350 °C.

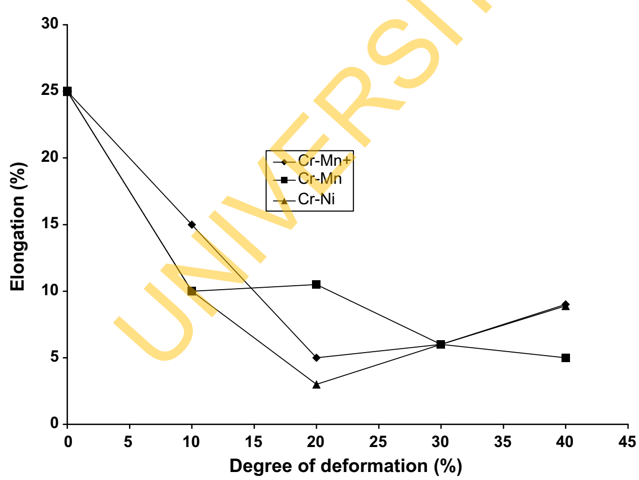


**Fig. 2c.** Variation of elongation with degree of deformation at 650 °C.

cation therefore, interacts elastically with the stress field around the obstacle (e.g., interstitial atom), and slippage in a given crystallographic plane is thus hindered. This amounts to strengthening, which is reflected as improved tensile strength and hardness or increased resistance to plastic deformation.

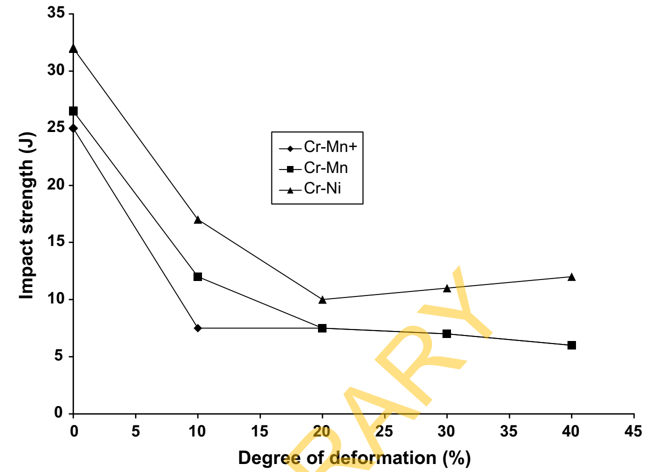


**Fig. 3a.** Variation of impact strength with degree of deformation at 28 °C.

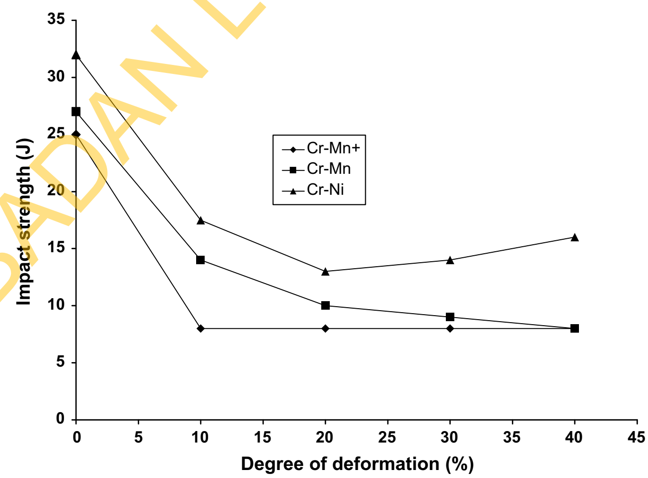


**Fig. 3b.** Variation of impact strength with degree of deformation at 350 °C.

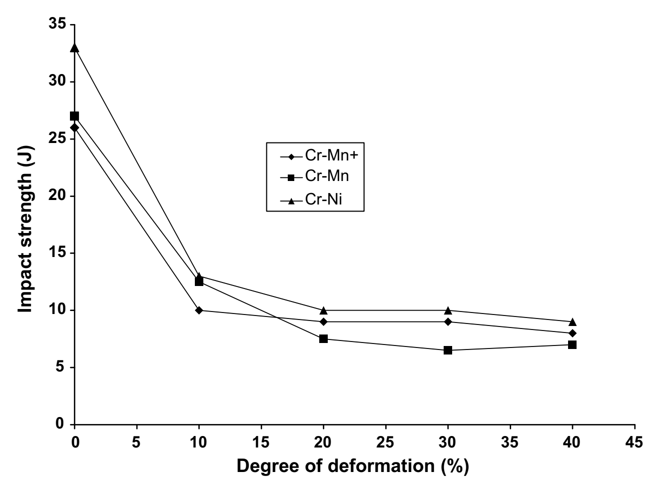


**Fig. 3c.** Variation of impact strength with degree of deformation at 650 °C.

Simultaneously, decrease in percentage elongation (Fig. 2a), and impact strength (Fig. 3a) was observed, because of the presence of internal stress, non-uniform dislocation structures and some quantities of ε-phase [20].

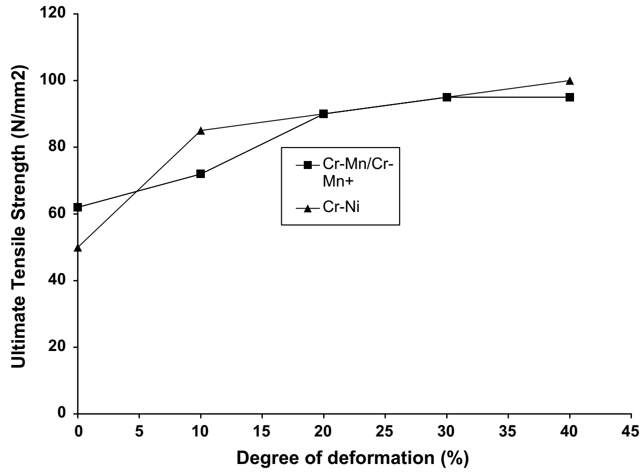


**Fig. 4a.** Variation of ultimate tensile strength with degree of deformation at 28 °C.

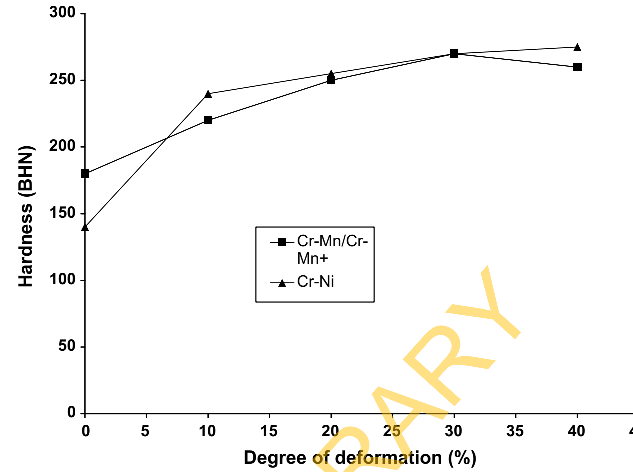


**Fig. 5a.** Variation of hardness with degree of deformation at 28 °C.

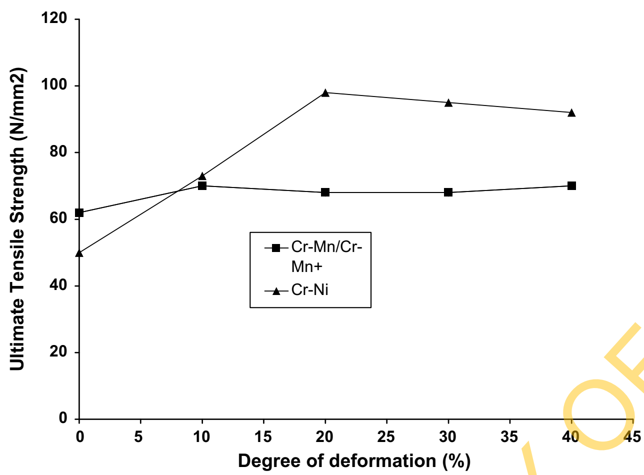


**Fig. 4b.** Variation of ultimate tensile strength with degree of deformation at 350 °C.

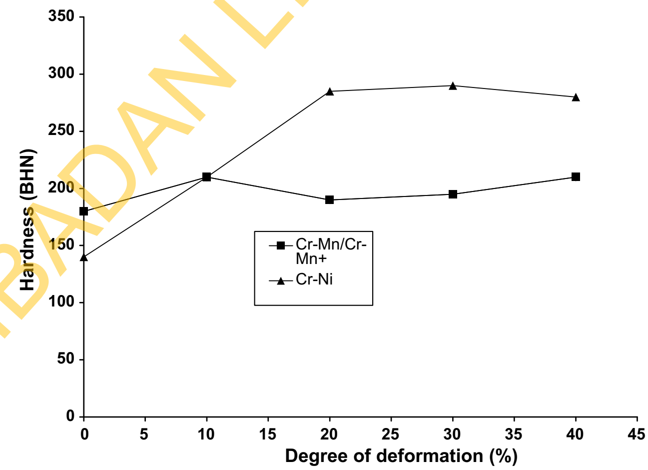


**Fig. 5b.** Variation of hardness with degree of deformation at 350 °C.

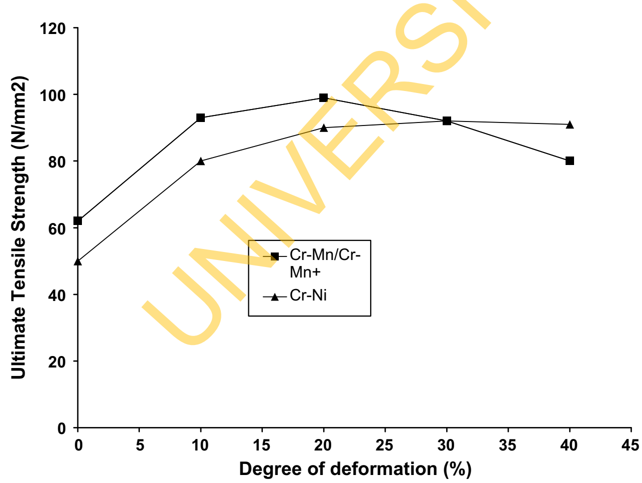


**Fig. 4c.** Variation of ultimate tensile strength with degree of deformation at 650 °C.

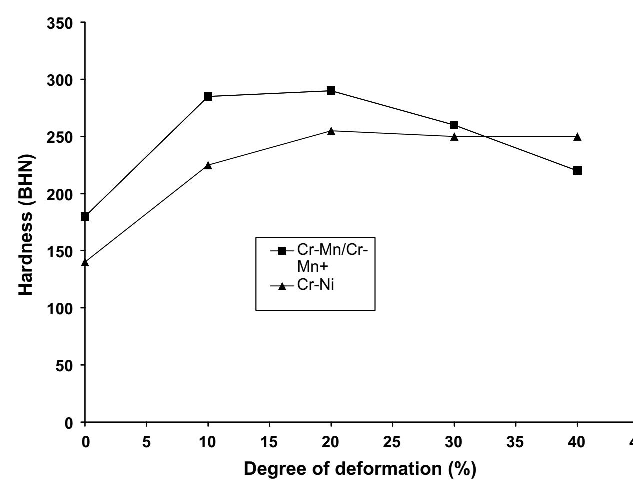


**Fig. 5c.** Variation of hardness with degree of deformation at 650 °C.

In order to bring further deformation in the metal (more than 10% deformation), greater loads were applied and slippage occurred along less favourably oriented planes of the metallic crystals. This gave rise to reduced rate of strengthening. Notwithstanding an overall strain hardening effect was experienced by the alloys. Furthermore, interaction among defects (dislocations) must have led to the formation of micro cracks [21], which impaired the plasticity of the alloys, as manifested in further reduction in the values of percentage elongation and impact strength, with increasing degree of deformation (Figs. 2a and 3a).

*3.2. Thermomechanical working at 350 °C*

Subjecting the austenitic steels to various degrees of deformation at 350 °C (warm deformation) produced some outstanding effects. The chrome–manganese austenitic steels showed tendencies for increased yield strength as the degree of deformation increased, while the chrome–manganese austenitic steel with no Ni and Mo addition showed better tensile strength and hardness values on the average than the Cr–Ni and Cr–Mn with Ni and Mo additions (Figs. 1b and 5b). The behaviour of the chrome–manganese austenitic steels rolled at this temperature with regard to ultimate tensile strength and hardness followed the same pattern. The plasticity of the steel types decreased with increasing degrees of deformation. However, the Cr–Ni austenitic steel showed better plasticity when compared to the chrome–manganese austenitic steels (Fig. 3b). The tendency for increased strengthening at 350 °C can be explained in terms of intensive dynamic recovery, annihilation of dislocations which usually accompany large strain and elevated temperature working or processing of alloys [4]. In other words, thermomechanical working at low temperature produced sufficient dislocation structure that culminated into highly improved tensile strength, with the impact energy or strength of the alloy not suffering a remarkable decline.

*3.3. Thermomechanical working at 650 °C*

Increasing the working temperature to 650 °C produced improvement in tensile properties, provided the degree of deformation do not exceed 20% ( Figs. 1c and 5c). Beyond 20% degree of deformation these properties tend to decline due to the process of dynamic ageing [3]. It suffices to remark here, that plasticity properties such as impact strength (toughness) and ductility normally decrease with increasing tensile properties [19]. The rate of decline of tensile properties with increasing degree of deformation beyond 20% is appreciable, while the rate of decline of rolling at 350 °C is near negligible, especially at 40% degree of deformation.

## 4. Conclusion

From the results it could be said that working at 350 °C produced better results especially with increasing degree of deformation, because higher plasticity values (toughness and ductility) are obtained at this temperature than those obtained at 28 °C and 650 °C.

It is therefore recommended that for effective strengthening, warm deformation at 300– 350 °C, and a degree of deformation between 20% and 30% should be employed for austenitic steels. It is suggested that split warm rolling employed in this work could be used as a mode of deformation.

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