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Influence of quenching and tempering heat treatment on tensile properties and toughness of cold-drawn 0.12wt% c steel

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Abstract

Low carbon steel of 0.12wt.% C steel cold drawn in 20, 25, 40, and 55% deformations of cold-drawn wires are characterised by brittle fracture when subjected to impact load because the process induces strain hardening. Experiments had been used extensively in industry to find the suitable heat treatment parameters for improved properties. The 0.12wt.% C steel was heated to the region of austenite and hold for 30 minutes and 40 minutes for comparison, then rapidly cooled SAE 10W-40 engine oil followed by tempering at 400deg. C. The yield strength of the drawn 25%, 40% and 55% steel reduce. The tensile strength reduces drastically for all the degree of cold-drawn steel. This was as a result of the dissolution of the steel carbon contents into the ferrite phase when heated above the AC_1 *temperature range and the tendency of the grain to grow due to prolong heating above recrystallisation temperature range. The impact toughness of the samples improves for the treated steel at 30 minutes duration of tempering reduces below the impact toughness of the non-treated steel for treatment at 40 minutes tempering duration for all the cold drawn steel. The toughness is also found to reduce with increasing cold drawn deformation and reduction rate tends to reduce with increasing cold-drawing. This procedure of heat treatment is extensively used for improving the toughness and hardness of the carbon steel. The study demonstrated the possibility of predicting the tensile and yield strength of 0.12% wt. C steel. The correlation relationship established that the interdependence of the strength and the hardness is more reliable at low tempering duration of 30 minutes compared with the duration at 40 minutes.*

Keywords: Tensile strength, yield strength, quenching, SAE oil, tempering, hardness, toughness.

Introduction

The carbon metals harden during drawing process and causes reduction in the ductility of the metal but increases its strength[1]. The hardness is caused by generating dislocation and its movement within the structure of the carbon metal. This effect is known as work hardening and also known as strain hardening. Strain hardening is the increment in internal energy due to the increased dislocation density and density in vacancies and interstitials[2,3]. The changes in the mechanical properties of the metal as a result of the deformation often influence the performance of the resulting product of the process in service.

Heat treatment for steel improves the mechanical properties of the steel. These properties include the yield strength, toughness, ductility, hardness and impact strength[4-6]. The various heat-treatment processes appropriate to plain-carbon steels are: normalizing, annealing, hardening, and tempering.

Quenching involve heating the steel up to the region of the austenite and then rapidly cooled either in air, water or oil. The quenching procedure is used to obtain the martensite phase of the steel. Investigation of the impact of cold reduction size and annealing on the mechanical properties of High Strength Low Alloy steel (HSLA) was attempted[7]. Also, investigation into the effect of tempering on the internal friction of carbon steel established that when metals are plastically deformed the internal friction increases and the elastic modulus decreases[8]. The elastic modulus could be recovered by heat treatment of such deformed meta. The dislocation density and mobility usually depend upon the intensity of tempering. The increase of the tempering time reduces the martensite tetragonality due to the carbon segregation from the interstitial sites towards the dislocations.

The quenching heat treatment is found in the design of products such as land tilling blades, shafts, punches, and crankshaft including hardening of welded joints. In Adedayo et al.[9] it was established that although hardness and toughness were dependent on the carbon content of the steel, there was also significant microstructural modification due to quenching. Casagrande *et al.*[10] predicted the fatigue stress value of steels using Vickers hardness measurements and different annealed, quench and tempered alloys were tested.

The quenching and tempering heat treatment also had been successfully used in the treatment of tools used for forming process. The variation of the microstructure of Vanadis 10, a powder metallurgy processed tool steel was investigated[11].

The investigation shows that destabilization of austenite is favoured by high tempering temperature of about 600ºC. However, quenching does not have a significant effect on the hardness of this steel but high temperature tempering had been found to improve hardness of some other metal properties of weld metals[12].

The possibility to predict yield strength, strength limit, fatigue live estimation as well as other mechanical properties depending on values of materials hardness is commonly known and it is often used in practice[13]. The relationship between hardness of a material and its strength could be determined by means of the hardness test[14]. A review of the possibilities of application of correlation relationships between hardness and ultimate tensile strength of steel sheets in various structural states was well documented[13]. The experiments were performed on steels with structure which is composed from ferrite and martensite (dual phase steels).

Petruška and Janı́ček[15] observed that large plastic deformation of cold formed metal is followed by its hardening, which can be experimentally evaluated by measuring hardness. To convert the measured hardness values into strain, the strain–hardness reference curves were used. Their evaluation is traditionally based on compression tests of cylindrical specimens. New procedure of reference curves evaluation was suggested based on Finite Element (FE) simulation of a forming process and direct relation of computed strain and measured hardness.

Casagrande et al.[10] predicted the fatigue limit of steels by using Vickers hardness measurements. Tests were carried out in small regions of different annealed, quenched and quenched-tempered alloy steels. In this method, the plastic deformation caused by the indentation of the Vickers hardness experiment was assumed to be the defect from which the process of initiation and propagation of cracks originate, analogously to small cracks. Fatigue limits for four kinds of steels in different metallurgical states (annealed, quenched and quenched-tempered) were estimated in two different ways, and the obtained values were compared to the experimental ones. A good correlation between Vickers hardness and the fatigue limits estimated by direct plastic deformation zone measurements using optical microscopy was envisaged.

Materials and methods

Materials: Specimen: 0.12wt.% C steel of 5.5mm diameter was used in this study. The chemical composition of the 0.12 wt.% C steel investigated is presented in Table-1. The steel was cold-drawn in a series of drawing dies reducing the wire diameter from 5.5mm to 5mm, 4mm, 3.3mm, and 3mm representing respectively 20%, 25%, 40 % and 50% degree of deformation as is applicable for the manufacture of the 4 inches, 3 inches, 2½ inches and 2 inches plain nails respectively. Seven hundred and twenty (120) samples (30 for each degree of cold-drawn wire), each of length 45mm were used for the experiments.

Table-1 : Chemical composition of the as-received steel wire (% wt.).

Element	C	Si	Mn	P	Fe
%	0.12	0.18	0.14	0.7	98.86

Equipment: The following equipment were used for the study.

A Muffle furnace, Gallenkomp® model SVL-1009 with voltage regulation of 220V, 50Hz of temperature range 300-1000°C was used for the heat treatment process. An Instron® 3369 testing machine equipped with an electro-mechanical sensor for control of tensile strain in the active zone of samples in the load range up to 50kN was used for the tensile test experiment. The Hounsfield balance impact machine and the Optical Microscope with image capturing device. The 810-163A HV-112 Vickers hardness tester was used for the hardness test experiment.

Methods: Heat treatment: The samples were heated in the muffle furnace to temperature of 900 ºC followed by soaking for 30 minutes and 40 minutes and then quenching in SAE 10W-40engine oil and then tempered at temperature range 400 – 600ºC for 30 minutes each then allowed to cool in air. This was to investigate the influence of quenching and tempering heat treatment on the mechanical properties of the 0.12wt.% C steel cold-drawn to 20%, 25%, 40%, and 55% degree of deformation at different tempering temperatures.

Mechanical test: Three basic mechanical property tests were conducted to obtain the properties of the heat treated cold-drawn 0.12wt.% C steel in service. These are the tensile test, Charpy impact test and the Vickers hardness test. The tests were carried out on three different samples for each of the cold drawn steel specimens of the 20%, 25%, 40% and 55% deformation at each tempering temperature and the mean of the measurement were taken.

Tensile Test: The specimens of diameters 5mm, 4mm, 3.3mm, and 3mm were cut to lengths of 45mm for purpose of the tensile tests. The tensile tests were done at room temperature on an Instron® 3369 test machine. The testing machine is equipped with a sensor which is electro-mechanical in nature. The electro-mechanical control was for control of the strain resulting from the tensile test for a load range of 25kN.

Charpy Impact Test: The relative toughness for the different heat-treated specimens of 5mm, 4mm, 3.3mm and 3mm cold-drawn 0.12wt.% C steel were determined from the Charpy-impact tests. A v-notch of 45º angle was cut on each specimen using a Hounsfield notching machine ensuring that the notch screw is set at a depth of 1mm so that the cutter just touches the test piece. Each test piece is broken with a pendulum on the Hounsfield balanced impact machine and the energy absorbed in fracturing is measured.

Hardness test: Hardness test was performed by indentation. The indenter is pressed on the carbon steel with a load of 50 N for 15 seconds and the depth of the indenter measured.

Results and discussions

Figure-1,3 shows the variation of the tensile properties and the impact toughness with percentage degree of cold-drawn deformation for the quenched sample at 900ºC soaked for 30 minutes and 40 minutes and tempered at 400ºC.

The yield strength of the 25%, 40% and 55% cold-drawn steel reduces when the steel is treated at 900ºC for soaking time of 30 minutes and 40 minutes and quenched in Society of Automotive Engineers (SAE) 10W-40 oil and tempered at 400ºC. The reduction in the yield strength tends to progress with the soaking time as shown in Figure-1a.

The yield strength also reduces with increasing deformation but slowly between the 25% and 55% degree of cold-drawn deformation. This is also evident as shown in Figure-2. However, the yield strength for the treated 20% cold-drawn sample increases compared to the non-treated sample. This could be attributed to the prolong recovery process associated with the 20% cold-drawn steel as observed when heat treated at 900ºC[16].

The tensile strength reduces drastically as observed in Figure-1b for the 20%, 25%, 40% and 55% deformation of the steel. This observation is in contrast to the hardening influence that quenching has on metals. However, this could be agreed to be due to the dissolution of carbon contents of the steel into the ferrite phase when heated above the AC_1 temperature range and the grain growth tendency due to prolong heating above the recrystallisation temperature range[17].

The toughness of the samples improves for the treated steel at 30 minutes soaking time but reduces below the toughness of the non-treated steel for treatment at 40 minutes soaking time for all the degree of cold drawing as shown in Figure-1c. The impact toughness is also found to reduce with increasing degree of cold drawing and the rate of reduction tends to reduce with increasing degree of cold drawing.

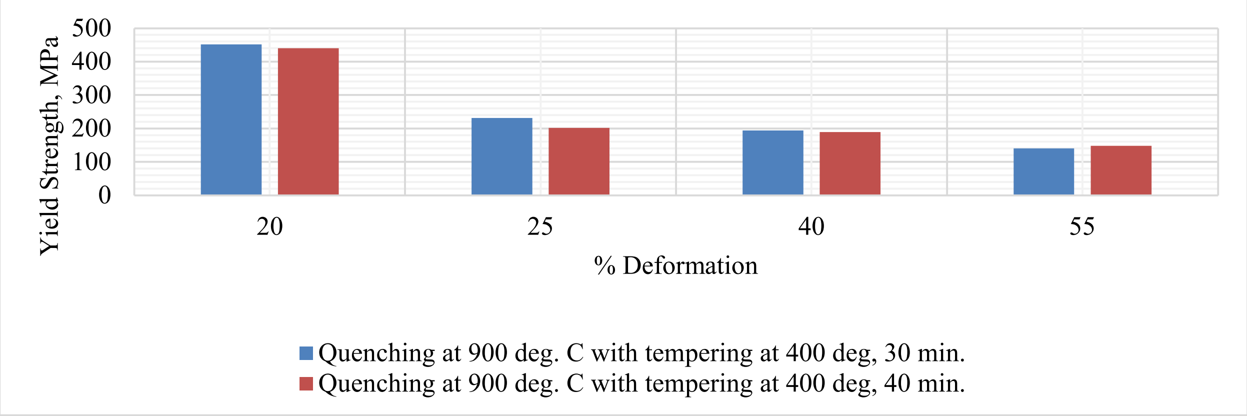

Figure-1: Yield strength property relation with % deformation for quenched and tempered steel

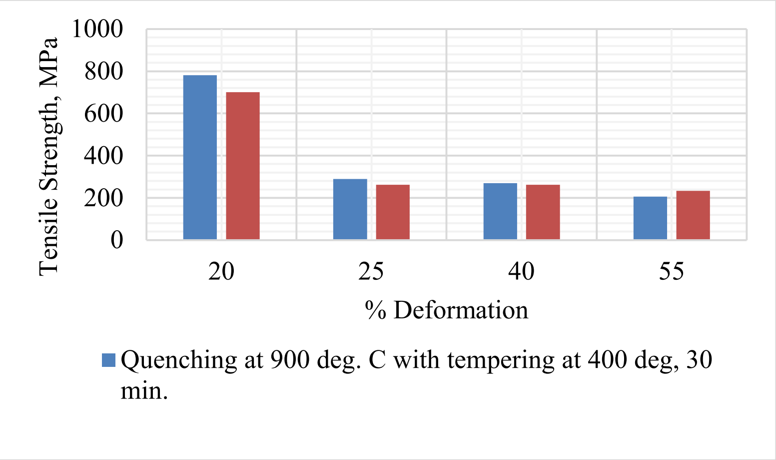

Figure-2: Tensile strength property relation with % degree of cold-drawn deformation for quenched and tempered steel.

The yield strength and tensile strength has correlation with the treated steel hardness as shown in Figures-4 and 5. The coefficient of correlation for the tensile strength relationship with hardness is found to be higher than the coefficient of correlation for the yield strength relationship with the hardness values. The interdependence between the strength and hardness of the steel can be considered relatively high as exposed in the R^2 values of 0.975 and 0.994 for the tensile strength and yield strength for 30 minutes tempering time respectively. However, at 40 minutes tempering duration the interdependence of the strength and hardness for both the tensile and yield strength is low with R^2 values of 0.80 and 0.84 respectively. The implication is that the increase in tempering duration could have reduced the martensite tetragonality due to the carbon segregation from the interstitial sites towards the dislocations. This implies that the prediction of the strength of 0.12 % wt. C based on its hardness at higher tempering duration could be erroneous and should be avoided. The coefficient of correlation reduces with duration of tempering in this case. The relationship is however suitable for the prediction of the yield strength as compared with the tensile strength.

The least square regression correlation for the tensile strength and yield strength after tempering for 30 minutes are obtained as expressed in equations (1) and (2) respectively.

$$UTS = -3923.4 + 27.584H \quad (1)$$

$$YS = -1985.2 + 14.332H \quad (2)$$

Figure-6 shows the relationship between the tempering temperatures and the hardness of the steel. It is observed that the hardness of the 0.12% wt. C steel decreases slowly between tempering temperatures of 400ºC and 500ºC for all the degrees of deformation. However, the hardness of the steel reduces rapidly at temperature above 500ºC.

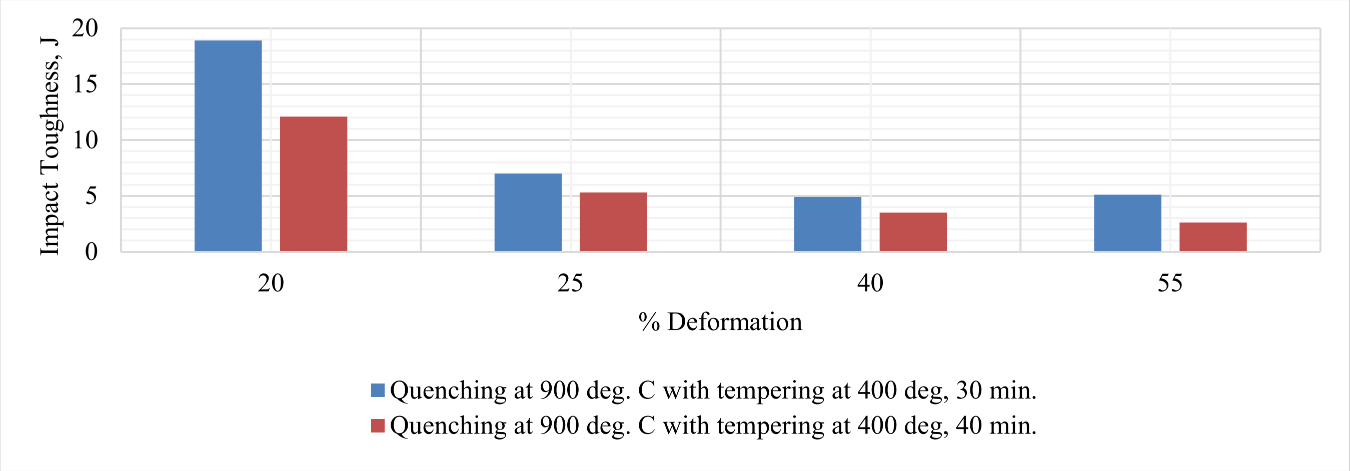

Figure-3: Impact toughness property relation with % degree of cold-drawn deformation for quenched and tempered steel.

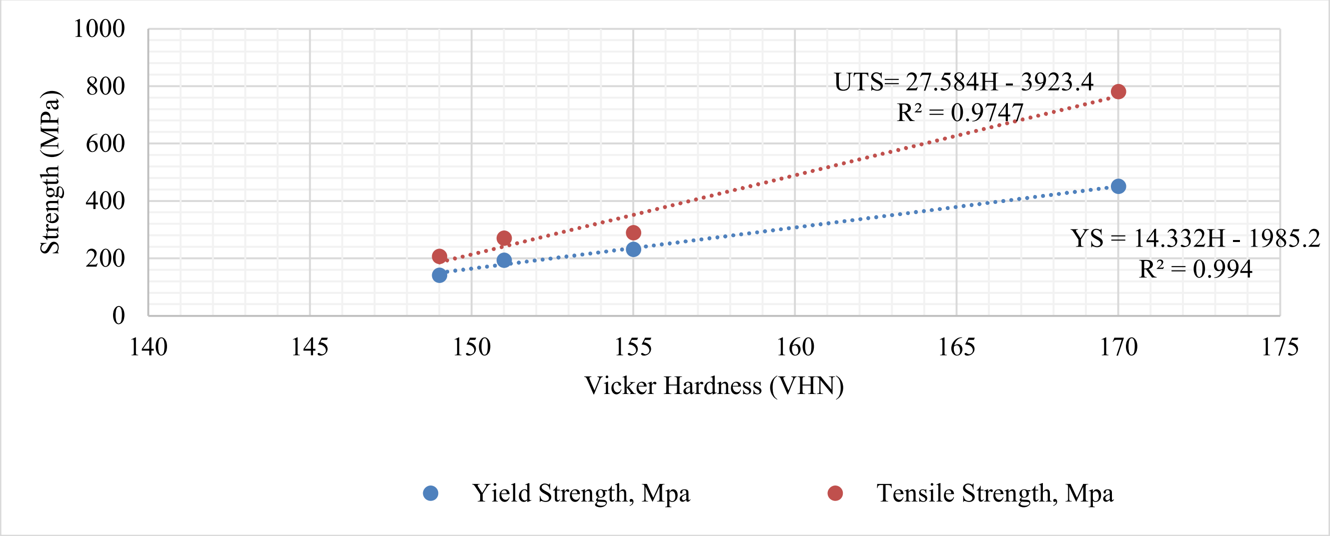

Figure-4: Plot of strength of 0.12%wt. C steel tempered at 400 deg. C for 30 minutes as a function of hardness.

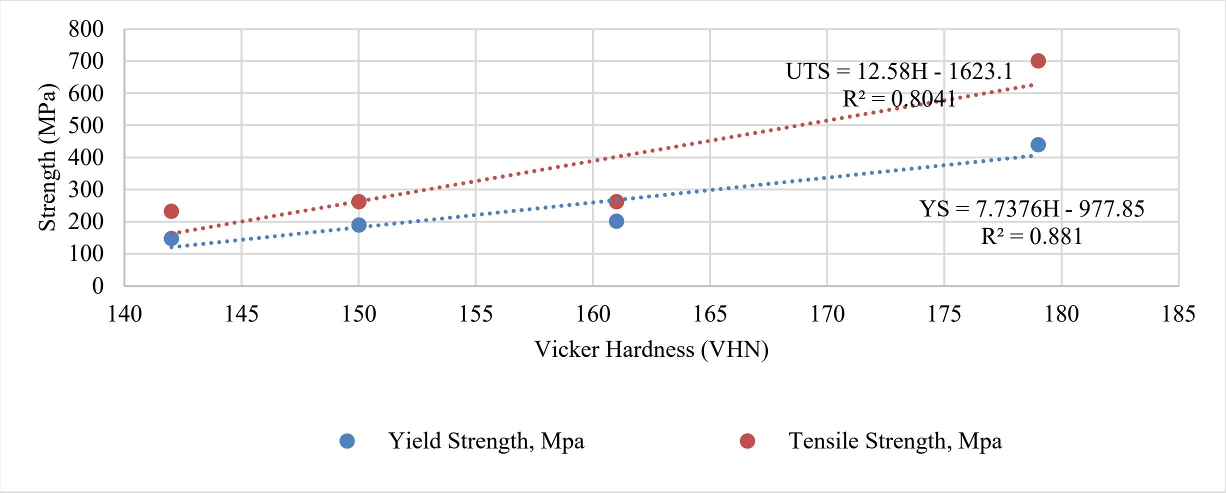

Figure-5: Plot of strength of 0.12%wt. C steel tempered at 400 deg. C for 40 minutes as a function of hardness.

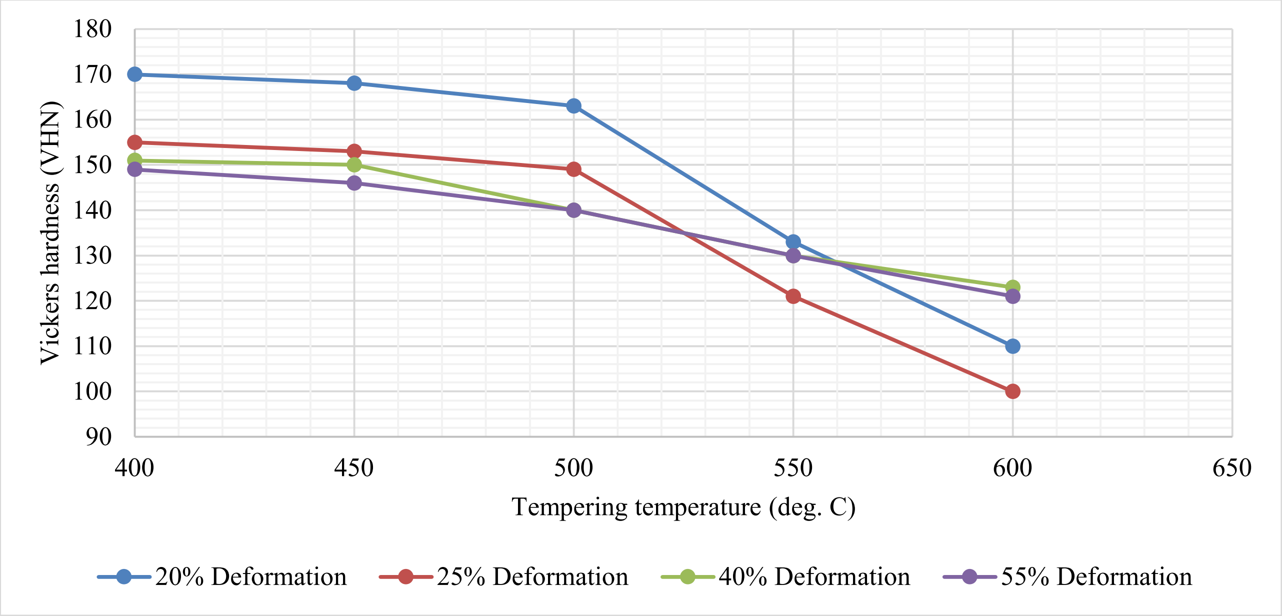

Figure-6: Hardness relationship with tempering temperature of 0.12% wt. C steel.

It could be inferred that at low temperature, the tempering only relieves the internal stresses and this usually contributes to reduction of the brittle nature of the cold drawn steel while most of the steel hardness is retained. The hardness of the steel reduces rapidly at higher temperatures for reduced tensile and yield strength.

Conclusion

The influence of the quenching and tempering heat treatment on the yield and tensile strength including toughness of the cold drawn 0.12wt.% C steel was investigated. The study shows that the quenching process which is cost effective could be used to improve not only the surface hardness of the steel but the toughness and improve ductility using the SAE 10W-40 engine oil medium. The quenching treatment is suggested for the treatment of steel-welds and fatigue loading engineering components such as the steering racks of automobiles. The quenching and tempering process is found to effect toughening by lessening the brittleness of the drawn steel and also reduces the internal stresses within the drawn steel structure. The study demonstrated the possibility of predicting the tensile and yield strength of 0.12 %wt. C steel. The correlation relationship established that the interdependence of the strength and the hardness is more reliable at low tempering duration of 30 minutes compared with the duration at 40 minutes.

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