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Study of the Mechanical Properties by Using Thermo-Mechanical Processing of Alloy Steel

Dr. Amin D. Thamir* , Dr. Mohammed H. Hafiz*
& Mahdi Mutar Hanoon*

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Abstract

The purpose of this work is to study the effects of thermo mechanical treatments to improve mechanical properties of the alloy steel (DIN 42 Cr Mo4), such as tensile strength, toughness, and hardness. All mechanical factors affected by the metallurgical changes in alloy like microstructure refinement and appearing new phases are thoroughly discussed.

Heating was done in induction furnace at 1150oC and specimens were forged in temperature of 1000oC but the forging process was done with different forging loads (deformation percentage) with values of (800, 1000, 2500 and 4000 tons) with a deformation percentage of (26%, 31%, 45% and 61%) respectively.

تحسين الخواص الميكانيكية باستخدام المعاملة الحرارية الميكانيكية للفولاذ السبائكي

الخلاصة

تكمن الغاية من البحث دراسة تأثير المعاملات الحرارية الميكانيكية العالية لتحسين الخواص الميكانيكية لسبيكة الفولاذ (DIN 42 Cr Mo4) ، كمقاومة الشد ، المتانة والصلادة. تتـأثر جميـع عوامل التآكل والعوامل الميكانيكية بالمتغيرات الميتالورجية كالتنعيم الحبيبي وظهور الأطوار الجديدة التي تم مناقشتها بشكل تفصيلي.

تمت عملية التسخين في فرن حراري حثي وبدرجة حرارة 1150 درجة مئوية ومن ثم تـم طرق العينات بدرجة حرارة مقدارها 1000 درجة مئوية لكن بأحمال طرق مختلفـة وهـي (800، 1000، 2500، 4000 طن) وبمكبس طرق وكانت نسب التشـكيل (26%، 31%، 45% و 61%) على التوالي.

أجريت الفحوصات الميكانيكية لجميع لعينات قبل وبعد المعاملة الحرارية الميكانيكية، والتي تضمنت فحص أجهاد مقاومة الشد ، فحص الصلادة وفحص المتانة. أفضل خواص ميكانيكة تم الحصول عليها وذلك عند أستخدام حمل طرق مقداره (1000 طن) أي بنسبة تشكيل مقدارها (31%) حيث كانت مقاومة أجهاد الشد 755 نيوتن/ملم^2 وبصلادة مقدارها HV215 ومتانة بقيـــــمة 41.3 جول.

*Production Engineering and Metallurgy Department, University of Technology/ Baghdad

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

Introduction

1. Thermomechanical Treatments

Thermomechanical treatment involves the simultaneous application of heat and a deformation process to an alloy, in order to change its shape and refine the microstructure. Thus, hot-forging of metals, a well-established industrial process, is a thermomechanical treatment which plays an important part in the processing of steels.[2]
Anther definition of TMT is that the plastic deformation of the initial austenitic matrix and the formation of its controlled structural and mechanical state with subsequent heat treatment, phase transformation. This link makes it possible to utilize the hardening or refining of the grains of the initial austenitic matrix and also the structural modification of the products of the phase transformation of austenite associated with the modification of structural and substructural characteristics of the austenitic matrix leading to a higher level of the set of the mechanical and metallurgical properties of various types of structural steel processed by this treatment.[3]

If plastic deformation of austenite takes place in the region of suppression of recrystallization, the subsequent phase transformation is also accompanied by the intracrystalline nucleation of ferrite grains leading to its more intense development and also to higher stability of untransformed austenite. This effect leads to the formation of islands of martensite or bainite in subsequent cooling. Therefore, from this viewpoint, it may be concluded that the intracrystalline nucleation of ferrite leads to two opposing effects: a) to a reduction in the ferritic hardenability in connection with a higher density of potential nucleation sites for ferrite grains; b) to an increase in the 'hardenability' of the matrix because of the higher stability of austenite.

Depending on the chemical composition and the cooling rate, three types of phase transformation and the associated formation of three types of microstructures take place during the subsequent phase transformation after forming.[4]

1. The ferritic phase transformation takes place in the non-hardenable steel or at the conventional cooling rates; this results in the formation of a fine-grained ferritic structure.
2. If the steel with medium hardenability is cooled at a slightly higher rate, two types of phase transformation take place: a diffusion phase transformation and a phase transformation of the shear nature leading to the formation of acicular ferrite.
3. In hardenable steels, or when using accelerated cooling, two separate phase transformation processes take place: ferritic and martensitic (or bainitic) with the formation of a two-phase structure. [5]

There are three types of thermomechanical treatment as below:

The process known as ausforming

or low temperature thermomechanical treatment (LTMT), involves the deformation of austenite in the metastable bay between the ferrite and bainite curves of the TTT diagram. The treatment is shown schematically in Fig. (1.a). Steel, with a sufficiently developed metastable austenite bay is quenched from the austenitizing temperature to this region, where substantial deformation is carried out, without allowing transformation to take place. [6]

The deformed steel is then transformed to martensite during quenching to room temperature, and the appropriate balances of mechanical properties are achieved by subsequent tempering.

This ausforming treatment can be contrasted with a high temperature thermomechanical treatment (HTMT), where the deformation is carried out in the stable austenite region (Fig. 1.b), usually above Ac3 prior to quenching to form martensite. In a third process, isoforming (Fig. 1.c), the steel is deformed in the metastable austenite region, but the deformation is continued until the transformation is complete at the intermediate temperature. The steel can then be slowly cooled to room temperature.[6]

Steels, in which austenite transforms rapidly at subcritical temperatures, are not suitable for ausforming. It is necessary to add alloying elements which develop a deep metastable austenite bay by displacing the (TTT) curve to longer transformation times. The most useful elements in this respect are chromium, molybdenum, nickel and manganese, and allowance must be made for the fact that deformation of the austenite accelerates the transformation. Consequently, it is necessary to have sufficient alloying element present to slow down the reaction and avoid the formation of ferrite during cooling to the deformation temperature.[7]

In high temperature thermomechanical treatments the deformation is carried out in the stable austenite range just above Ac3 (Fig. 1.b), and so can be performed in steels, which do not possess a suitable metastable austenite bay. The steel is then quenched to the martensitic state and tempered at an appropriate temperature. [9]

The strengthening achieved arises from austenite grain size refinement, typically from 10-60 μm to 3 μm, but optimum properties are often obtained if recryslallization of the austenite is avoided. As in ausforming strong carbide forming elements are beneficial, which suggests that alloy carbide precipitation occurs in the austenite during deformation. A particular advantage of this process is that optimum properties can be achieved at modest deformations (≈40%) so that deformation can be carried out more readily on existing equipment. The HTMT process does not yield as high strengths as in ausforming but the ductility and fatigue properties are usually superior.[10]

Its main objective is to achieve microstructural refinement to produce ultra high strength, improved ductility, and greater toughness in a wide variety of finished and semifinished steel or nonferrous products [11].

As in the case of steels for ausforming, the chosen steel must have a suitable (TTT) diagram. First, it is necessary to be able to deform the austenite prior to transformation, then the transformation must be complete before deformation has ceased. Only modest increases in strength are achieved. However, there can be a very substantial improvement in toughness due to the refinement of the ferrite grain size and the replacement of lamellar cementite by spheroidized particles. Finally, care must be taken to restrict deformation to temperatures at which the ferrite and pearlite reactions take place, as similar deformation in the bainitic region leads to marked reductions in toughness.[12]

2. Experimental Work

2.1 Material:

Raw material used was (DIN 42CrMo4) alloy steel used in the form of rods which were assembled into specimens of dimensions (30 mm and lengthof L = 285mm).The chemical composition of the material is listed in Table 1.

This steel alloy is used for many of applications like component of automotive , gear and engine , e.g. crankshafts , steering knuckles , connecting rods , spindles , intermediate gears and pump shafts.

Mechanical properties of steel alloy used in this research which was quenched and tempered are as follow:

Yield point : 765 N/mm^2
Tensile strength : 980 – 1180 N/mm^2
Elongation : 11 %
Redaction of area : 45 %
Impact energy : 41 J
Hardness HV: 172

2.2 Thermomechanical Treatments

In this research thermomechanical treatments achieved heating specimens in induction furnace (I/P 358 kvA 525v 394A 50Hz from company AEG-ELOTHERM) to temperature of (1150 ^{o}C) for four minutes.

After heating to desired temperature, heated specimens were moved from induction furnace to close die forging press machine Figure (3). During handling of hot specimens the temperature went down to 1000oC when forging operation was done.

The forging operation for specimens used classified to four pressing loads as given in table (2). When forging operation was completed, the specimens were cooled in air at the room temperature.Forming percentage for each specimen was different from another, depending on forging loads

Forming percentage calculated for forged specimens for specimen (1) are shown in Figure (4):

2.3 <u>Tests</u>

After all (TMT) was completed for the four specimens and the fifth specimen which was as fabricated, the sampling operation started by cutting specimens to desired shapes for each test as given below:

Tensile tests

Tensile specimens were sampled from the end of the deformed side as shown in figure (5) and figure (6) shows dimension of tensile specimen according to ASTM E 8M:

After finishing tensile specimens, the test was accomplished by computerized tensile machine D-

22881 Barsbüttel / Germany wp300 with maximum tensile force of 200kN.

Toughness Calculations:

The Toughness test was carried out from the area under the curve for tensile test (load-deformation) for each specimen.

Hardness test

Hardness test was done by using (Digital Hardness Equo-Tip Portable) for the same microstructure samples after regrinding and polishing them.For each sample there were five hardness readings tacked, and their values were divided by five to obtain the average value.

Micro-examination Test

The as received specimens and specimens subjected to thermomechanical treatments were sectioned to samples with dimensions of (ϕ 20 and thickness of 10 mm) by water cooled cutting machine, then grinded by using silicon-carbide grinding papers with grit No. of (120 , 220 , 300 , 500 , 800 , 1000 and 1200). After deep cleaning with water to remove grinding particles from the surface of samples, polishing was applied in two stages, first with alumina with particle size of 5 µm, followed by alumina with P.S. of 0.3 µm. After completing polishing each sample was washed with distilled water carefully.

Final stage for microexamination preparation test was etching, it was done with prepare an etchant solution composed of (2% HNO3 + 98% glycerin) this etchant agent was used instead of nital due to low viscosity of nital which fill porosity of micro-holes formed by hard and brittle chromium-carbides removed by surface preparation and damaged surface after final cleaning when remained in these holes, while the used etchant had high viscosity which will not enter in micro-holes of surface.

After completing etching which was done by immersion, cleaning was done by washing with distilled water then with high purity alcohol, and the samples were dried finally.

Optical metallurgical microscope (EP-Type II, Germany) was used to examine samples, it was connected to Digital Camera (Type: Sony W130).

3. Results and Discussion

3.1 The Effects of Forging Variables on the Mechanical Properties

The mechanical properties of (DIN42CrMo4) alloy steel are considered as follows. The tensile test has been done for as received steel and the treated alloys. To determine the effect of deformation percentage on tensile strength for alloy (DIN42CrMo4), tensile test was done for all specimens as shown in table (3).

Tensile strength increases with T.M.T. percentage up to (31%) after this value the tensile strength decreases as shown in figure (7), where deformation percentage is a very important factor which changes the metallurgical phases as shown in. Figures (10– 14). Increasing of deformation percentage leads to precipitating carbides as achieved by X-Ray Diffraction tests and microstructure photographs which increase hardness as shown in figure (9) and tensile strength as in figure (7). In 26% of forming (T.M.T.) percentage there is increase in mechanical properties by precipitating ($(FeCr)_7C_3$) as shown in Figure (11), and when deformation (T.M.T.) percentage value is (31%) there is precipitation of ($(FeCr)_7C_3$+$(FeCr)_2C$) shown like small dark spots in Figure (12), this leads to increasing in mechanical properties more than in forming (T.M.T.) of (26%), because the combined phases ($(FeCr)_7C_3$+$(FeCr)_2C$) have more hardness of ($(FeCr)_7C_3$). Where the forming (T.M.T.) percentage value exceeds (31%) a grain size of alloy is greater due to high internal energy which leads to accelerating recrestilization and grain growth of a metal, these phenomena lead to significant decrease in mechanical properties except toughness as shown in Figure (8) where the decrease is little. The toughness increases with ductility which is increases beyond (31%) deformation (T.M.T.) and it decreases with increasing of hardness.

In general manner the combination of changing mechanical and metallurgical properties after forming percentage higher than (31%) causes slight decrease in toughness value.

The toughness of each sample has been estimated by computing the area under the curve.

These values of the deformed (DIN 42CrMo4) alloy steel compared with undeformed (DIN 42CrMo4) alloy steel are listed in Table (3). Figure (8) shows the effect of deformation percentage on the toughness.

3.2 Forging Structural Changes

Figure (10) shows the (DIN42 Cr Mo4) alloy steel microstructure before T.M.T. process, when this microstructure is observed two phases can be seen when tested in X-ray diffraction. The first is α- iron (α-Fe) and (second phase) are perlite (α+Fe_3C) the mean grain size was (5µm) for all structure and with hardness of (HV=172).

When the alloy steel of this work was heated at austenitisation temperature of 1150C°, the carbon dissolved and the austenite grain size was increased.

During the air cooling from the metastable austenite to deformation temperature of (1000°C) and forging load of 800 ton Figure (11). The X-ray diffraction was done, there are three phases introduced, the first was chromium carbides ($(FeCr)_7C_3$) and the second phase was bianite we were think that appear like large grains of (66µm) , and finally the third phase was a matrix of martensite we think that have fine grain size of (3µm). The exist of these three introduced phases causes the hardness to increase to HV=203.

Also this (DIN42 Cr Mo4) alloy steel used in this work contains the carbide-forming elements like (Mo) that is extracted carbon from solution in austenite and tends to form numerous nucleation sites for undissolved fine dispersion of alloy carbides precipitation or iron carbides during cooling to room temp. , and thus helps to raise the strength of steel.

Hence after the hot working the

steel was air cooled by continuous cooling to room temp. , the bainite package forms as granular bainite containing fine alloy carbides precipitation, with smaller nodule sizes of carbides, and ferrite, also austenite was retained, in a matrix of martensite.

All the previous illustrations are confirmed by the XRD analysis and microstructure examination of the specimens.

Figure (12) shows the alloy steel microstructure with forging load of 1000 ton , two main phases appear in X-ray diffraction, the first was matrix of matrinsite and the binaite and the second is [$(FeCr)_7C_3$],the matrix have the grain size 4μm this will increases in hardness to reaches (HV= 215).

When the alloy steel (DIN42 Cr Mo4) was forged with forging load of 2500 ton Figure (13), the microstructure and X-ray diffraction analysis shows three phases present, the first is chromium carbides ($(FeCr)_7C_3$) due to depletion of chromium and the second was bianite the third is ferrite with iron chromium carbides which is called alloyed (Fe-Cr). This third phase is the main phase and it is responsible for hardness drop of the whole alloy steel whose hardness becomes (HV=184), and the main grain size is 20.2 μm.

Finally Figure (14) shows the microstructure of (DIN42 Cr Mo4) alloy steel which was forged to load of 4000 ton. When Thermomechanically processed alloy was tested with X-ray diffraction, the two phases appear the first is pearlite ($\alpha+Fe_3C$) and the second phase was of chromium carbides ($(FeCr)_7C_3$). The microstructure shows two region the first was matrix with very large grain size of (71μm) with low hardness and the second was small spots which appear like black regions. with hardness was (HV= 157)

4. Conclusions

1. The T.M.T. operation caused changes in microstructure of the phases and grain size.
2. Increasing forging load (deformation percent) lead to decreasing in grain size of (DIN 42 Cr Mo4)alloy but the reverse is not proportional always, the grain size begins to increase when the load exceeds 1000 ton (deformation of 31%) and decreased some of mechanical properties like hardness.
3. With respect to transformation process new phases were obtained such as, (upper and lower binite + martensite) in addition to fine carbides precipitation, ferrite and retained austenite some of Cr-carbides could be also observed as small black spots. These spots increase the hardness rapidly but decrease the ductility. Finally combination of these phases enhances mechanical properties of the alloy used in this work.
4. The optimum deformation percent value, (31%) showed maximum mechanical properties (tensile , hardness and toughness). i.e. (755MPa , 215 HV and 41.4J) respectively.

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Table (1) Chemical composition of steel investigated. Wt.%

Steel 1.7225 as in AISI		Chimical Comp. for tested Metal	
Element	Wt. %	Element	Wt. %
C	**0.38-.45**	**C**	**0.42**
Si	**0.15-0.4**	**Si**	**0.29**
Mn	**0.5-0.8**	**Mn**	**0.70**
P	**0.035**	**P**	**0.03**
S	**0.035**	**S**	**0.06**
Cr	**0.9-1.2**	**Cr**	**0.93**
Mo	**0.15-0.3**	**Mo**	**0.17**
Ni	0.60	Ni	0.54

Table (2) Forging loads , percentage deformation, temperature and heating time for the specimens.

Specimen No.	Forging Temperature oC	Heating Time Min.	Load (Ton)	Forming Percentage %
1	**As it is**	**---**	**---**	**---**
2	**1000**	**4**	**800**	**26**
3	**1000**	**4**	**1000**	**31**
4	**1000**	**4**	**2500**	**45**
5	**1000**	**4**	**4000**	**61**

Table (3) Mechanical properties

Sample No.	**Forming Percentage %**	**Yield stress (MPa)**	**Tensile Strength (MPa)**	**Toughness (J)**	**Hardness Hv**
1	Without Deformaton	509.30	625	18.10	172
2	26	582	730	38.20	203
3	31	550	755	41.30	215
4	45	524	725	35.80	184
5	61	520	710	29.04	157

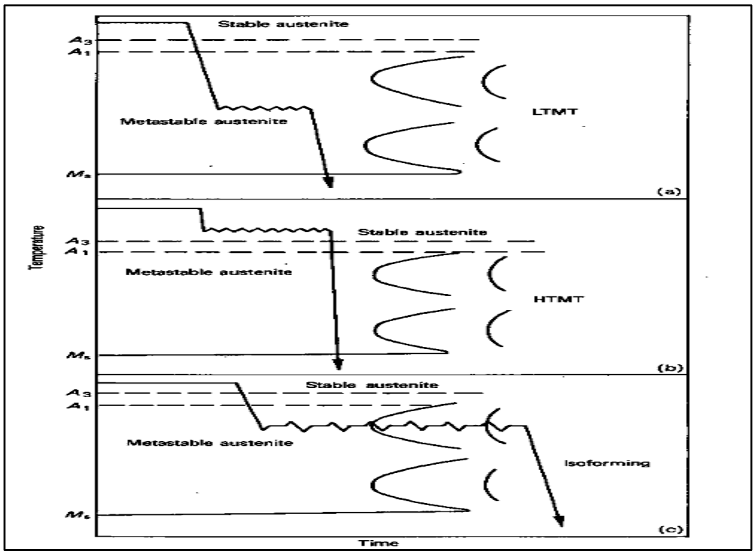

Figure (1): Schematic diagrams of thermochemical treatment[6]:
a) Ausforming-low temperature mechanical treatment.
b) High temperature mechanical treatment.
c) Isoforming transformation.

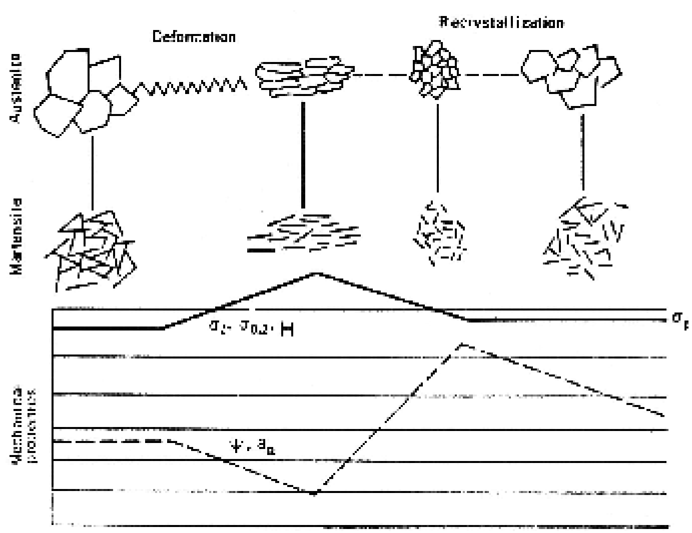

Figure (2) Effect of high-temperature thermomechanical treatment on mechanical properties of steel[13]

Figure (3) Close Die forging pressmachine.

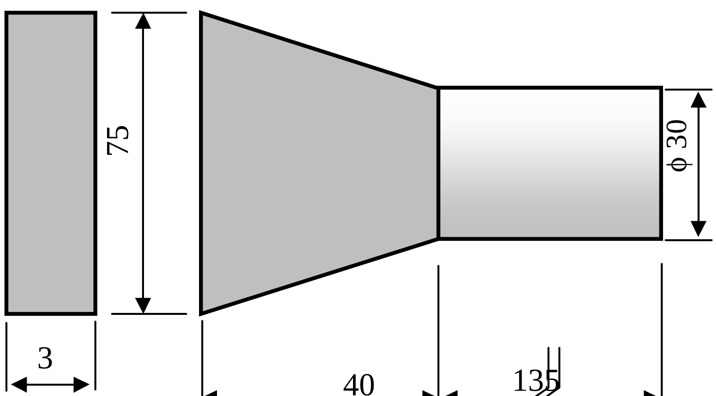

Figure (4): Specimen (1) Dimensions after TMT.

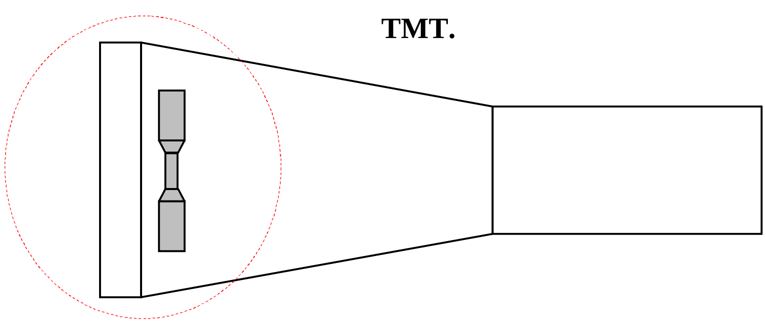

Figure (5): Location of the sampled tensile specimen

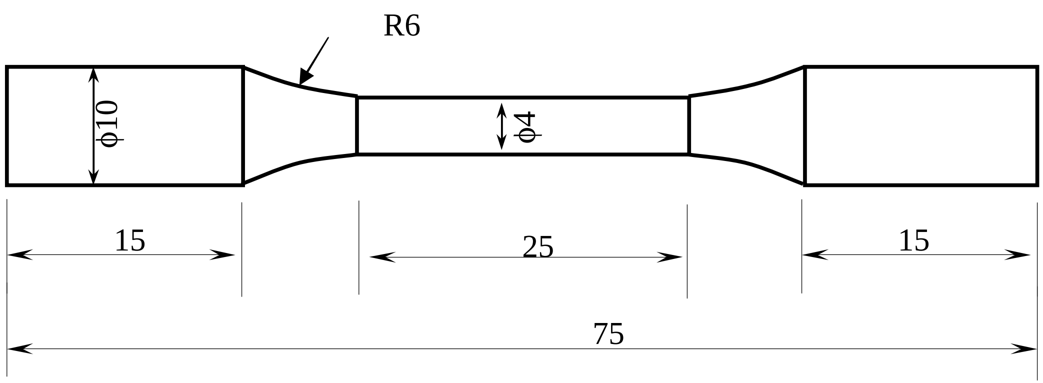

Figure (6): Tensile specimen (all Dim. in mm).

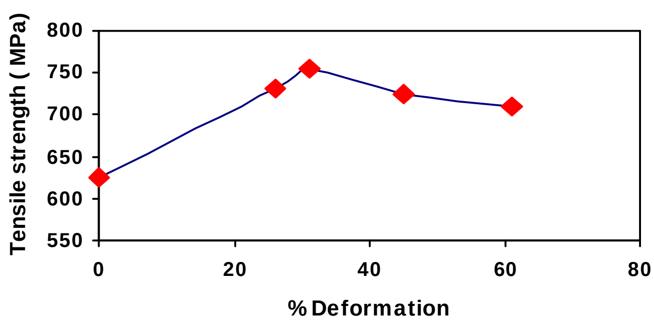

Figure (7) Effect of deformation percentage on the tensile strength.

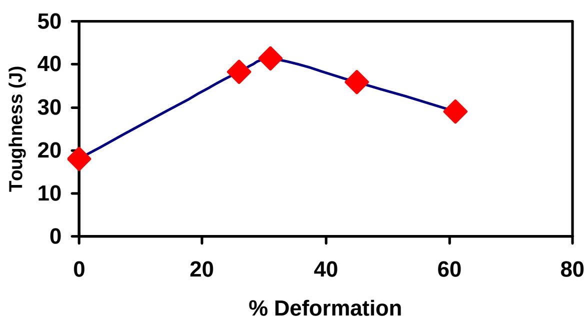

Figure (8) :Effect of deformation percentage on the toughness.

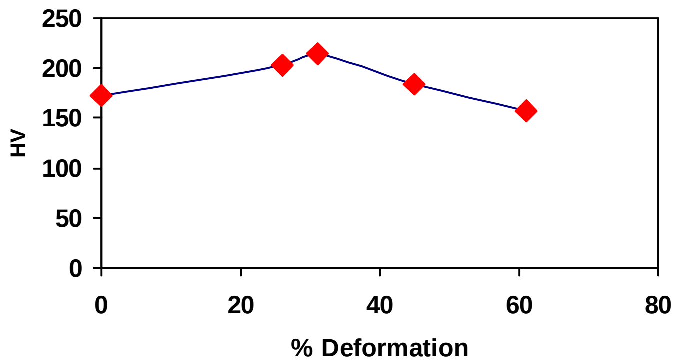

Figure (9): Effect of deformation percentage on the hardness.

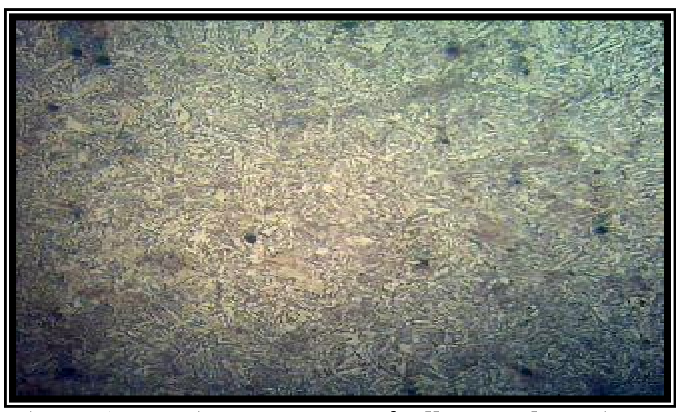

Figure (10): Microstructure of Alloy Steel specimen Before T.M.T. [X 300], two fhases {(α-Fe), (*p* (α+Fe_3C)) } Grain size = 5 μm

Figure (11): Microstructure Alloy Steel specimen forged with load 800 ton. [X 300] the structure is matrix of three phase {(($FeCr_7C_3$) , Bianite, and Martensite} L Grain size = 66μm S Grain size = 3 μm

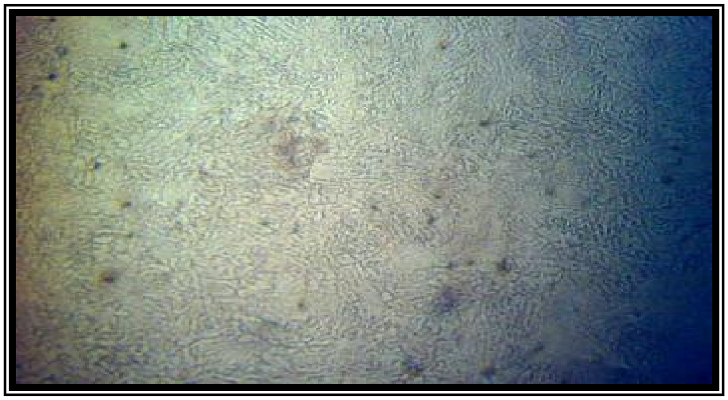

Figure (12): Microstructure Alloy Steel specimen forged with load of 1000 ton [X 300], two fhases { Bianite$(FeCr)_7C_3$, Martensite} , Grain size = 4 mm

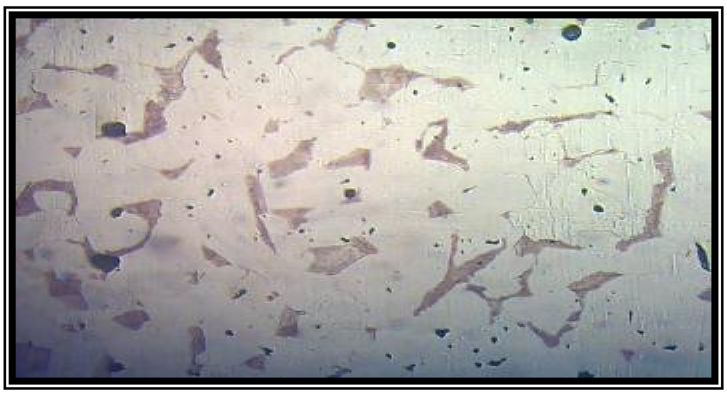

Figure (13): Microstructure Alloy Steel specimen forged with load of 2500 ton [X 300], three fhases{(Fe-Cr), Bianite, $(FeCr)_7C_3$}, Grain size = 20.2 mm

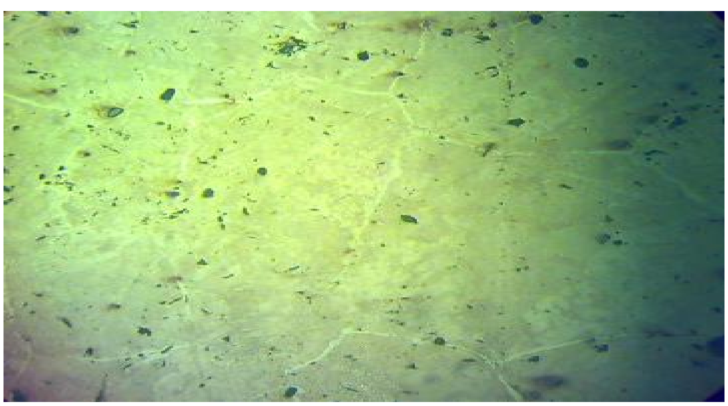

Figure (14): Microstructure AlloySteel specimen forged with load of 4000 ton. [X 300] , two fhases { perlite $(a+Fe_3C)$, (FeCr) }. Grain size = 71.4 mm