

Mechanical properties and structural evolution during Warm Forging of Carbon Steel

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Abstract- Warm forging is the plastic deformation of a metal at temperatures below the recrystallization temperature range and above room temperature; typically in the temperature range of 600-900°C. Warm working combines the advantages of both cold and hot working. Compared to cold/hot forging, warm forging offers the advantages of fewer forming steps as a result of greater workability, reduced loads, energy savings, high material utilization. This work has done on En 24 and 1018 low carbon steel to establish quantitative knowledge of mechanical properties occurring during the warm working at the temperature of 800°C with the help of different processing parameters (amount of deformation, soaking time and strain rate). The paper shows that the hardness, toughness and strength increases with increase in deformation after warm forging. It also affects the toughness value. Microstructure along with volume percentage of retained austenite also estimated to get proper explanation for high or low toughness. Finally optimum forging and parameters are used to impart the benefits of warm forging than cold or hot forging for carbon steel.

Index Terms- Warm Forging, Hardness, Toughness, Strength, Low Carbon Steel.

I. INTRODUCTION

Warm forging is the plastic deformation of a metal at temperatures below the recrystallization temperature range and above room temperature; typically in the temperature range 0.3-0.6 of the melting temperature (T_m).

In steels, however, due to the occurrence of blue brittleness around 0.3 T_m the warm working range usually quoted is 0.5-0.65 T_m ; between 600-900°C. Ferrite brittleness and scaling factor is limiting for this working temperature range. Warm working involves the heating of the material to the working temperature and deforming it at that temperature. This is distinct from other processes such as controlled rolling where the material is deformed at a higher temperature followed by finishing deformation in the warm working temperature range [1].

In the recent past there has been growing interest in warm working with the aim of combining the advantages of both cold and hot working, primarily regarding forging. Compared to cold forging/rolling, warm working offers the advantages of fewer forming steps (i.e. a reduced number of dies in forging) as a result of greater workability, reduced loads due to higher deformation temperatures, energy savings due to elimination of in-process annealing treatments and high material utilization from cold and hot forging [1].

As the carbon percentage content rises, steel has the ability to become harder and stronger through heat treating; however it becomes less ductile. Regardless of the heat treatment, higher carbon content reduces weldability. In carbon steels, the higher carbon content lowers the melting point [2].

In practice, warm working has been shown to be an economical manufacturing method for forging precision parts that are (a) difficult to cold work because of workability or press-capacity limitations, or (b) cannot be hot worked because of surface finish or dimensional requirements. Ceramic inserts and coatings are well established in the machining industry for reducing tool and die wearing. It is very difficult to maintain the forging temperature throughout the process. High-speed warm forging is very limited. However, the full potential of warm working has not yet been utilised, particularly in rolling, due mainly to a poor knowledge of the metallurgical and operating parameters. Warm working cannot simply be carried out by applying the established practice of cold or hot working at an appropriate intermediate temperature, it requires a technology of its own. The implementation of warm forging is limited by high investment costs for the rearrangement of machines and expenses for tools and development. Consequently a large volume of work has been carried out in the last twenty years on various aspects of warm working technology. Warm forging is a relatively new process that became known in early 70s. While it is more established in the industry of East-Asian countries and Japan, warm forging is not used wide spread in Europe [3].

Steel undergoes a metallurgical phase transformation at temperatures within or slightly above the warm-forging range. This transformation is associated with a change in volume distinct from that which is due to purely thermal effects. It occurs over a range of temperature that is dependent on alloy content. Depending on the requirements of a particular application, the warm-forging temperature may be below, within, or above the transformation temperature range. With respect to ferrous materials, warm forging is becoming more and more common as a means of increasing precision [4].

Deshpande et.al [5] have studied the Selection of die materials and surface treatments for increasing die life in warm forging. The dies are subjected to high contact pressures and temperatures. The selection of the die material, hardness and coating is critical for increasing die life in warm forging. Die life increases by use of ceramics, carbides and super alloys and surface treatments.

V Soleymani et.al [6] have studied the grain refinement in a low carbon steel through multidirectional forging. Grain refinement is one of the successful and low-cost methods to develop metals having excellent combination of strength and ductility. Low carbon steel was deformed by using multidirectional forging (MDF) technique at room temperature. The influence of strain amount and annealing process on the microstructure and mechanical properties of investigated steel was studied. The grain refinement mechanism was studied by the microstructure observation.

In warm-forging, the flow stress becomes very complex with the change of temperature, strain, and strain rate. Among these factors, the influence of temperature is most significant. Thus a proper forming temperature range is very important in warm-forging, which will be helpful in reducing forces and work energy, eliminating defects, and advancing the metal flow [7].

II. EXPERIMENTAL PROCEDURE

Material used- (i) EN-24 low alloy steel (ii) AISI 1018 low carbon steel

Composition of EN-24 low alloy steel-

Carbon	0.4%	Silicon	0.2%
Nickel	1.5%	Manganese	0.5%
Chromium	1.2%	Phosphorous	0.04%
Molybdenum	0.3%	Sulphur	0.03%

Typical Mechanical Properties of EN-24 as shown in table no.1

Table 1: Mechanical Properties of EN-24

Ultimate Tensile (N/mm ²)	Yield (N/mm ²)	Elongation %	Toughness Joule (Upto 150mm sample size)	Hardness Brinell
850-1000	650	13	50	248-302

Composition of AISI 1018 low carbon steel-

Carbon	0.18 %	Phosphorous	0.04 %
Iron	98.81%	Manganese	0.7 %
Sulphur	0.05%		

Typical Mechanical Properties of AISI 1018 low carbon steel as shown in table no.2

Table 2: Mechanical Properties of AISI 1018 low carbon steel

Ultimate Tensile N/mm ²	Yield strength N/mm ²	Elongation %	% Area reduction	Toughness Joule (Upto 150mm size of sample)	Hardness Brinell
440	370	15	40	17	285

Size of the billet cut: Billet having 40mm diameter of both the steel were taken for warm forging at 800°C temperature and cut according to the required length of sample for warm forging as obtained by the calculation.

III. CALCULATION

Volume of the raw material = Volume of the sample after warm forging

$$\pi R^2L + 10\% \text{ scale loss of raw material volume} = \pi r^2l$$

$$11 \div (10 \pi R^2L) = \pi r^2l \dots\dots\dots \text{equation (i)}$$

Here, R=Raw material sample radius =20mm, r= forged sample radius, L=Length of raw sample, l=Length of forged sample=120mm

Here deformation has done by reducing the diameter and elongate the length of the sample. Here we have to find out ‘L’.

In case of 30% deformation forged sample radius (r) = 14mm, then from (i) L≈54mm.....equation (ii)

In case of 40% deformation forged sample radius (r) =12mm, then from (i) L≈40mm equation (iii)

IV. EQUIPMENTS USED

After heating in electric muffle furnace both samples were forged in two different forging equipments (i) Pneumatic hammer and (ii) Hydraulic press. The details of these equipments are given below.

Capacity- 250kg (max.)
Company Name- New standard engineering Co. Ltd. (India) and B.S. Massey Ltd.(England).
No. of blow/minute-140

Pneumatic hammer- The pneumatic hammer is the most inexpensive and versatile type of equipment for generating load and energy, to carry out a forging process. It is most commonly used forging equipment, especially in forging of steel, in small and medium size production lots. During a working stroke, the deformation proceeds until the total kinetic energy is dissipated by

plastic deformation of the forging stock and by plastic deformation of the ram and anvil, when the die faces contact with each other. A typical pneumatic hammer was used in this process as shown in fig.1.



Fig.1: Pneumatic hammer

Hydraulic press- Hydraulic presses are operated by large pistons driven by high-pressure hydraulic or hydro pneumatic systems. The basic difference between hydraulic press and other methods is that pressure is applied in a squeezing manner rather than by impact. Hydraulic presses are two types; one is direct driven, which operate with hydraulic fluid (oil or water) pressurized directly by high-pressure pumps. Second one is hydro pneumatic presses, which operate with hydraulic fluid supplied from accumulators that are pressurized by high pressure pumps.

These machines are used for both open die or closed die-forging operations. In closed die forging of small and medium size parts, hydraulic presses are used either for preforming or for forging of aluminium and magnesium alloys, where die chilling does not present any problems. Most of the load is available during the entire stroke. So hydraulic presses are ideally suited for extrusion type forging operations requiring nearly constant load over a long stroke. A typical hydraulic press has used for this process as shown in fig. 2.



Fig.2: Hydraulic press

Unit-lb/sq. inch
 Pressure-4480lb/sq. inch
 Capacity- 6000lb/sq. inch
 Make- Fielding & Platt Ltd.,

Electric muffle furnace- It is an electric resistance furnace in which a refractory envelop surround by the electric coil and electrode provides the necessary heat through eddy current flow when power is applied to the primary coil surrounding the charge. This furnace operates noiselessly. The furnace involves high operational costs. A typical electric muffle furnace was used in this process a shown in fig. 3.



Fig.3: Electric muffle furnace

Name-Iherelek
 Heating capacity- 1300°C

V. FLOW CHART OF EXPERIMENTAL PROCEDURE

Experimental procedures have done according to the flow diagram as shown in fig. 4.

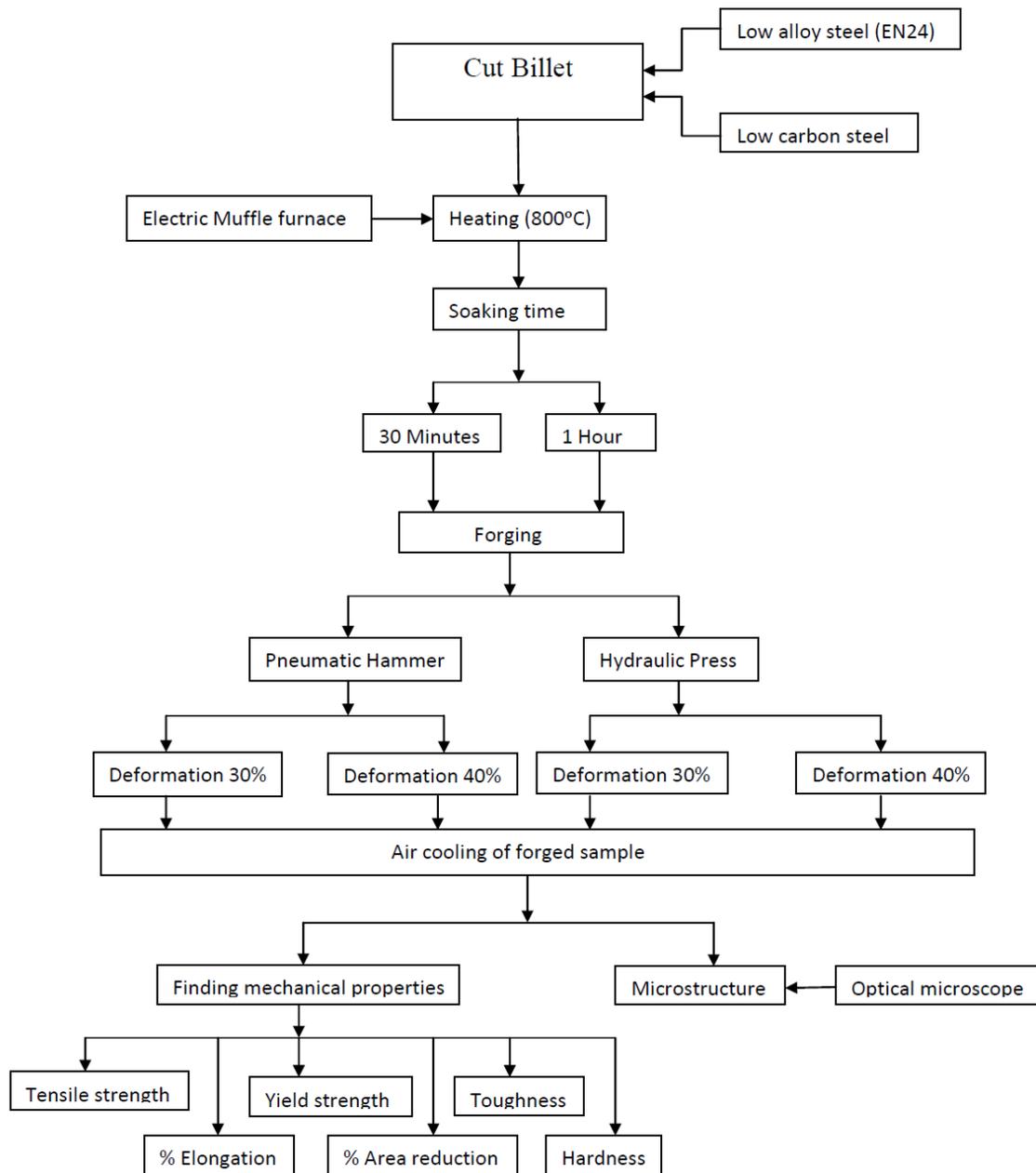


Fig.4: Flow chart of experimental procedure

VI. DESCRIPTIONS OF EXPERIMENTAL PROCEDURES

The billet was cut for warm forging of low alloy steel EN-24 and AISI 1018 low carbon steel as per the required dimension. Then it was heated in electric muffle furnace at 800°C with two different soaking time 30 minutes and 1 hour. Now forging has done with two different rate of deformation, 30% and 40% in two different equipments, pneumatic hammer and hydraulic press of each samples. Then forged samples were cooled in air. After that mechanical properties (UTS, yield strength, % elongation, % area reduction, toughness, hardness) have found out.

Mechanical properties:

Tensile test- A universal tensile testing machine as shown in fig.5 has used for tensile test. A test almost universally employed to express mechanical properties and to supply the most useful fundamental information regarding the behaviour of materials is the tensile test. Before commencing the test two gauge marks are made on the specimen longitudinally. The ends of the test piece are then gripped in the tensile testing machine and gradually increasing load is applied until failure is approached. The amount of elongation in the test piece caused by the load is measured by extensometer. As the loading of the test piece progresses, loads and deformation readings are recorded.



Universal tensile testing machine model no.- 52/191
 Make- Switzerland
 Capacity- 10 Ton

Fig.5: Universal Tensile Testing Machine

The dimension of the standard sample for tensile test piece has taken with gauge length =60mm, length =120mm, radius =5mm which are shown in fig. 6.

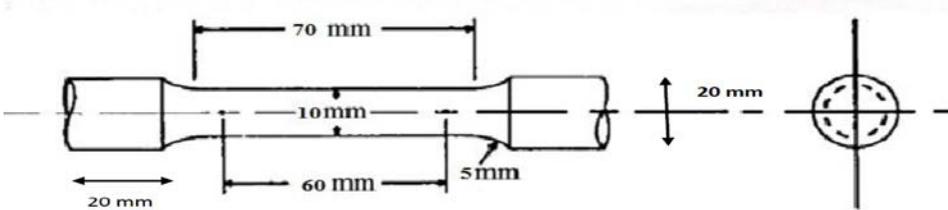


Fig. 6: Tensile test piece with dimension

Sample size-

- For 40% deformation-(i) 40mmX40mm (Φ)...(for tensile test piece)...from(iii)
- (ii)20mmX 40mm (Φ)...(for impact test piece)..from(iv)
- For 30% deformation-(i) 54mmX40mm (Φ).....(for tensile test piece)...from(ii)
- (ii) 25mmX 40mm (Φ)....(for impact test piece)...from(v)

Now as the impact test piece is of square cross-section of side (say 'a')

Converting the above circular cross-section as mentioned for tensile test piece into a square cross-section of equivalent area.

Area of circle = area of square

$$\text{Or, } \frac{\pi}{4} \times d^2 = a^2$$

$$\text{Or, } a^2 = \frac{3.14 \times 28 \times 28}{4}$$

$$\text{Or, } a = \sqrt{\frac{3.14 \times 28 \times 28}{4}}$$

$$\text{Or, } a = 24.80 \text{ mm} \approx 25 \text{ mm} \dots \dots \dots \text{equation (iv)}$$

Similarly for 40% deformation

$$a = 21 \text{ mm} \approx 20 \text{ mm} \dots \dots \dots \text{equation (v)}$$

Formulae:-

$$\text{Ultimate Strength} = \frac{\text{maximum load}}{\text{original cross sectional area}} \dots \dots (1)$$

$$\text{Yield Strength} = \frac{\text{Yield point load}}{\text{original cross sectional area}} \dots \dots (2)$$

$$\text{Percentage elongation} = \left(\frac{\text{final length} - \text{initial length}}{\text{initial length}} \right) \times 100 \dots \dots (3)$$

$$\text{Percentage reduction in area} = \left(\frac{\text{initial area} - \text{final area}}{\text{initial area}} \right) \times 100 \dots \dots (4)$$

$$\text{Toughness} = \text{mass} \times \text{acceleration due gravity (g)} \times \text{difference of height} \dots \dots (5)$$

Capacity-30 kg
 Model No.-130/167
 40 divisions of scale on machine=3cm
 Make- Switzerland

Impact test- This test gives the toughness value of the material. Which signifies the amount of energy absorbed by a material at the time of fracture under impact loading, where a notched bar prepared as per standard from the test material, is held in a vice and a weight is allowed to swing from a known height in such a way that it hits the notched bar in its path and breaks it. Since the material has absorbed some amount of energy during its fracture, the swinging mass losses part of its energy and therefore will

not be able to reach the same height from where it started. The loss in height multiplied by the weight represents the energy absorbed by the specimen during fracture, which can be directly measured from the indicator on the tester. A typical Izod test machine has shown in fig.7 and a standard impact test piece as shown in fig.8.



Fig.7: Izod test machine

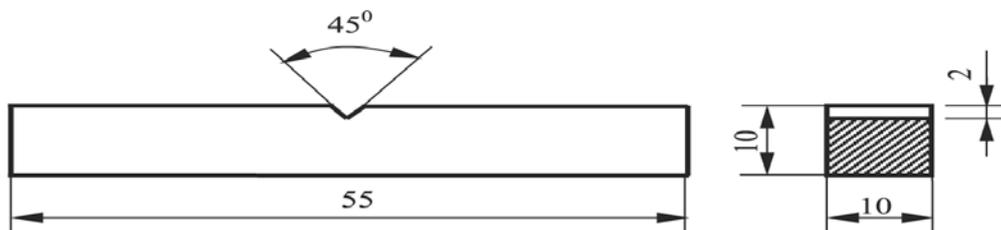


Fig. 8: Standard impact test piece sample

Hardness

With the help of Brinell hardness testing machine as shown in fig.9 hardness test has done of each sample. The Brinell hardness test method consists of indenting the test material with a 10mm diameter hardened steel to a load of 3000kg. For softer materials the load can be reduced to 1500kg or 500kg to avoid excessive indentation. The full load is normally applied for 10 to 15seconds in the case of iron and steel. The diameter in the indentation left in the test material was measured with a low powered microscope. The hardness value of the corresponding diameter of indentation was noted from the data table of BHN. Total 3 values of BHN have taken in 3 different locations on the sample and finally average value of all BHN values were calculated for all samples.



Fig. 9: Brinell Hardness Testing Machine

Max. Load- 3000 kg
 Min. Load- 250 kg
 Diameter of indenter-10 mm, Manufacturer-
 Mohr & Federheff AG Mannheim, West
 Germany

VII. RESULTS & DISCUSSION-

Variation of tensile properties for forged steel in pneumatic hammer:

Table no.3 shows the properties of 1018 low carbon steel at different rate of deformation with different soaking time as per given calculation in equation (1,2,3,4).

Table 3: Tensile properties of 1018 low carbon steel in pneumatic hammer

Soaking time	Deformation	Tensile properties			
		UTS MPa	Yield Strength MPa	%Elongation	%Reduction in Area
1 hour	40 %	541.1	363.06	20	46.71
	30%	518.61	358.85	20.33	39.16
30 minutes	40%	503.62	375.75	20.5	49.59

	30%	494.87	363.05	18.33	43.75
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Table no.4 shows the properties of EN-24 low alloy steel at different rate of deformation with different soaking time as per given calculation in equation (1,3,4).

Table 4: Tensile properties of EN-24 low alloy steel in pneumatic hammer

Soaking time	Deformation	Tensile properties		
		UTS MPa	%Elongation	%Reduction in Area
1 hour	40 %	1129.71	5.83	23.56
	30%	1093.47	5.00	21.43
30 minutes	40%	1114.71	5.83	27.75
	30%	1007.42	5.00	19

Variation of tensile properties for forged steel in hydraulic press:

Table no.5 shows the tensile properties of 1018 low carbon steel at different rate of deformation with different soaking time as per given calculation in equation (1,2,3,4).

Table 5: Tensile properties of 1018 low carbon steel in hydraulic press

Soaking time	Deformation	Tensile properties			
		UTS MPa	Yield strength MPa	%Elongation	%Reduction in Area
1 hour	40 %	506.23	369.23	21.66	46.71
	30%	497.3	349.42	13.33	43.75
30 minutes	40%	497.37	350.03	14.66	46.71
	30%	469.8	331.31	12.66	27.75

Table no.6 shows the properties of EN-24 low alloy steel at different rate of deformation with different soaking time as per given calculation in equation (1,3,4).

Table 6: Tensile properties of EN-24 low alloy steel in hydraulic press

Soaking time	Deformation	Tensile properties		
		UTS MPa	%Elongation	%Reduction in Area
1 hour	40 %	1163	5.33	27.43
	30%	1131	3.83	23.75
30 minutes	40%	1161.7	13.33	36
	30%	1149	3.33	22.56

A typical fig.11 shows the tensile test piece sample which have used to find out the tensile properties.



Fig.11: Tensile test piece

Variation of hardness of forged steel in hydraulic press:

Table no.7 shows the hardness of EN-24 low alloy steel at different rate of deformation with different soaking time.

Table 7: Hardness of EN-24 low alloy steel in hydraulic press

Soaking time	Deformation	Indentation dia.	BHN	Avg. BHN
1 hour	40%	3.5	363	355.66
		3.4	341	
		3.0	363	
	30%	3.25	302	346
		3.34	321	
		3.20	415	
30 minutes	40%	3.3	363	371.33
		3.4	388	
		3.3	363	
		3.2	341	

	30%	3.1	321	334.33
		3.2	341	

Table no.8 shows the hardness of 1018 low carbon steel at different rate of deformation with different soaking time.

Table 8: Hardness of 1018 low carbon steel in hydraulic press

Soaking time	Deformation	Indentation dia.	BHN	Avg. BHN
1 hour	40%	4.5	179	170.66
		4.6	170	
		4.7	163	
	30%	4.9	149	153.66
		4.8	156	
		4.8	156	
30 minutes	40%	4.5	179	188.33
		4.2	207	
		4.5	179	
	30%	4.7	163	165.33
		4.6	170	
		4.7	163	

Variation of hardness of forged steel in pneumatic hammer:

Table no.9 shows the hardness of 1018 low carbon steel at different rate of deformation with different soaking time.

Table 9: Hardness of 1018 low carbon steel in pneumatic hammer

Soaking time	Deformation	Indentation dia.	BHN	Avg. BHN
1 hour	40%	4.5	179	170.66
		4.6	170	
		4.6	170	
	30%	4.5	179	168.33
		4.7	163	
		4.7	163	
30 minutes	40%	4.5	179	217
		4	285	
		4.4	187	
	30%	4.4	187	193.66
		4.3	197	
		4.3	179	

Table no.10 shows the hardness of EN-24 low alloy steel at different rate of deformation with different soaking time.

Table 10: Hardness of EN-24 low alloy steel in pneumatic hammer

Soaking time	Deformation	Indentation dia.	BHN	Avg. BHN
1 hour	40%	3.2	363	379.66
		3.1	388	
		3.1	388	
	30%	3.2	363	341.66
		3.4	321	
		3.3	341	
30 minutes	40%	3.2	363	357.33
		3.4	321	
		3.1	388	
	30%	3.4	321	327.66
		3.4	321	
		3.3	341	

Variation of toughness of forged steel in pneumatic hammer

Table no.11 shows the toughness of 1018 low carbon steel at different rate of deformation with different soaking time as per given calculation in equation (5).

Table 11: Toughness of 1018 low carbon steel in pneumatic hammer

Soaking time	Deformation	Toughness (Joule)
1 hour	40	0.7
	30	0.5
30 minutes	40	0.8
	30	0.65

Table no.12 shows the toughness of EN-24 low alloy steel at different rate of deformation with different soaking time as per given calculation in equation (5).

Table 12: Toughness of EN-24 low alloy steel in pneumatic hammer

Soaking time	Deformation	Toughness (Joule)
1 hour	40	1.55
	30	1.25
30 minutes	40	1.60
	30	1.40

Toughness: Variation of toughness of forged steel in hydraulic press:

Table no.13 shows the toughness of 1018 low carbon steel at different rate of deformation with different soaking time as per given calculation in equation (5).

Table 13: Toughness of 1018 low carbon steel in hydraulic press

Soaking time	Deformation	Toughness (Joule)
1 hour	40	0.75
	30	0.50
30 minutes	40	0.80
	30	0.65

Table no.14 shows the toughness of EN-24 low alloy steel at different rate of deformation with different soaking time as per given calculation in equation (5).

Table 14: Toughness of EN-24 low alloy steel in hydraulic press

Soaking time	Deformation	Toughness (Joule)
1 hour	40	1.3
	30	1.2
30 minutes	40	1.6
	30	1.3

A typical fig.14 shows the Izod test sample were used to find out the toughness.

**Fig.14:** Izod test piece

VIII. RESULTS & DISCUSSION

As per the experimental data obtained after warm forging of EN-24 low alloy steel and 1018 low carbon steel at different parameters the properties of materials have changed.

The ultimate tensile strength, % elongation, % area of reduction, toughness and hardness of 1018 low carbon steel increases in case of 40% deformation in pneumatic hammer with 1 hour soaking time than 30% deformation with 1 hour soaking time.

In case of hydraulic press it was found that the toughness and hardness of 1018 low carbon steel increases in 40% & 30% deformation with 30 minutes soaking time than 40% & 30% deformation with 1 hour soaking time.

The ultimate tensile strength and hardness of EN-24 low alloy steel increases in case of 40% deformation in pneumatic hammer with 1 hour soaking time than 40% deformation with 30 minutes soaking time. But toughness decreases in case of 40% deformation with 1 hour soaking time than 30% deformation with 30 minutes soaking time in pneumatic hammer.

In case of 30% deformation with 1 hour soaking time the ultimate tensile strength, % area of reduction increases of EN-24 low alloy steel increases than 30% deformation in pneumatic hammer with 30 minutes soaking time. But the % elongation remains

same in this case. Here toughness increases but hardness decreases in case of 30% deformation in 30 minutes soaking time than 30% deformation in 1 hour soaking time.

In case of hydraulic press it was found that the ultimate tensile strength and toughness of EN-24 low alloy steel increases in case of 30% deformation with 30 minutes soaking time than 30% deformation with 1 hour soaking time. But hardness, % area of reduction and % elongation decreases in this case.

In case of hydraulic press it was found that the toughness, % area of reduction, % elongation and hardness of EN-24 low alloy steel decreases in case of 40% deformation with 1 hour soaking time than 40% deformation with 30 minutes soaking time. But the ultimate tensile strength increases in this case.

IX. CONCLUSION

As per the experimental data and microstructure obtained after warm forging its conclusion depends upon the following factors-

1. Soaking time
2. Amount of deformation
3. Forging equipments

Effect of soaking time-

- (i) Strength increases with increase in soaking time.
- (ii) Toughness decreases with increase in soaking time.
- (iii) Hardness decreases as well as increases with increase in soaking time at different amount of deformation with different strain rate.

Effect of deformation

The amount of deformation 40% gives some significant change in mechanical properties of the material than 30% deformation. Mechanical properties increases with increase the amount of deformation.

- (i) Hardness increases with increase in deformation.
- (ii) Tensile strength increases with increase in deformation in case of more soaking time and vice versa.

Effect of equipments used-

Because of different strain rate of hydraulic press and pneumatic hammer the mechanical properties changes.

- (i) In case of 1018 low carbon steel hardness decreases in hydraulic press.
- (ii) In case of EN-24 low alloy steel hardness increases in hydraulic press than pneumatic hammer.
- (iii) Tensile strength increases in case of hammer in 1018 low carbon steel than hydraulic press.
- (iv) Toughness increases in case of hammer.

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